TC
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FORM PRODUCTION PROCESS IN DIGITAL ARCHITECTURE:
Thinking, Modelling and Fabrication

An M.Sc THESIS

By

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Approval of the Institute of Research and Graduate Studies

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This is to certify that we have read the thesis named "FORM PRODUCTION PROCESS IN DIGITAL ARCHITECTURE: a Process Starting from Thought Ending with Application" which has done by Mr. Hatem Ahmed Ali Hadia, student no.: 0409030002, and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Architectural Design.

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ABSTRACT

FORM PRODUCTION PROCESS IN DIGITAL ARCHITECTURE:
Thinking, Modelling and Fabrication

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Along with the development of computer technologies and computer-aided design (CAD)/ computer-aided Manufacturing (CAM) technologies, digital tools are increasingly adapted in architectural design. Digital tools are no longer limited to two-dimensional drafting or final presentation; they have become tools that can assist design thinking and producing. The emerging of those tools opened up new opportunities by allowing the production and construction of very complex forms that were until recently very difficult to achieve. The consequences of the changes brought about by the introduction of CAD/CAM technologies in building design and construction are likely to be profound, as the historic relationship between architecture and its means of production is increasingly being challenged by new digitally driven processes of design, fabrication and construction.

With the emergence of new factors and standards of modern architecture such as body perceptions and smooth surfaces, architecture today has become unrestricted Contrary to what had existed previously. Where there is no restriction limits the formation of voids and coexistence with, in addition to the factors sensual of the human body is now possible to be one of the key elements for the formation of the void and architectural form in general. The integration of design, analysis, construction process by the aid of digital technology reduced the “gap between designing and producing that opened up when designers began to make drawings” as observed by Mitchell and McCullough, [1995].

The study attempts to trace the development of architectural form in the last decade, specifically focusing on form in digital architecture. It investigates the recently thoughts, methods and design process in digital architecture; also estimating the effects of technology on today's architecture.

Studying the form in digital architecture has been chosen for several reasons. Firstly, the improvement in the field of architecture can be realized on the new methods and design techniques which based on the three dimensional modeling and visualization. Thus; the emerging of these methods expands our abilities to create, to perceive, to express and compose architectural form. Secondly, the role of computer technology in architecture has gained a marked significance and led to a different approach to physical production/construction; so studying in this context would reconfigure the relationship between technology and production. Finally, above all, defining the process of digital design still somehow blurry to some designers, engineering and even the educated architects because of the gap between designing and production. Because of that; the study trying to finalize and reduce the gaps between designing and producing of digital form by reordering the early stages of the design process till the fabrication stage.

This research aims to understanding the procedures of architectural form by using the techniques of digital technology starting from thoughts ending with production. For instance; studying the recently thoughts of contemporary architects who are involving in the case of improving the form in architecture would clearly identify the form in digital architecture as well as the aid of digital technology for making any type of complicated form possible to be built. Thus; the research will finalize the tools and methods of digital form which used while creating any type of architectural form, also will summarize the digital fabrication procedures that made the form possible to build. the strategical study of the thesis will focus on the form from different view of studies; the first one is studying the importance and basic elements of architectural form. Secondly; understanding the new concepts, methods and techniques from the view of digital architecture. thirdly; Classifying digital design tools both in terms of design and fabrication. Then studying the digital Production process. Finally practcing digital form by analizing the recently thoughs and work of diferent architects.

Keywords: CAD/CAM, digital architecture; digital form; computer techniques in architecture; digital design tools; digital design method; digital chain; “CNC” computer numerical control; “RP” rapid prototyping; digital fabrication.

ÖZET

SAYISAL MİMARLIKTA BİÇİM ÜRETİM İŞLEMİ:
Düşünce, Modelleme ve Uygulama

Hadia, Hatem Ahmed
Mimarlık Yüksek Lisans; Mimarlık Bölümü
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Bilgisayar teknolojileri ve bilgisayar-destekli-tasarım (CAD)/ bilgisayar-destekli-imalat (CAM) teknolojilerinin gelişimiyle, mimari tasarımda sayısal araçların kullanımı artmıştır. Sayısal araçlar artık yalnızca iki boyutlu çizim ya da sunuş ile sınırlı değillerdir; tasarımda düşünmeye ve üretime yardım edebilen araçlar haline gelmişlerdir. Bu araçların doğuşu, çok karmaşık biçimlerin yakın zamana kadar oldukça zor olan üretimlerini ve inşasını olanaklı hale getirmek için yeni fırsatlar yaratmıştır. Bina tasarımı ve inşasında CAD/CAM teknolojilerinin başlamasıyla oluşan değişimin sonuçları, tasarım ile uygulama arasındaki tarihsel ilişki, yeni sayısal tasarım ve inşa işlemleri bağlamında bağlamında derinleşmektedir. Mitchell and McCullough [1995] a göre, sayısal teknolojinin yardımıyla tasarım, analiz ve inşa işlemlerinin birbirleriyle bütünleşmesi, tasarımcının henüz çizim yapma sürecinin başındayken tasarımlama ile üretme arasında oluşan uçurumu yok etmesini sağlanmaktadır.

Çalışmada, özellikle sayısal mimarlıkta biçim üzerine yoğunlaşmak üzere, geçen yüzyılda mimari biçimin gelişiminin izini sürmek amaçlanmaktadır. Yakın zamanda sayısal mimarlıkta gündemde olan düşünceler, yöntemler ve tasarımlama işlemleri araştırılmakta; aynı zamanda teknolojinin bugünün mimarlığı üzerindeki etkileri göz önünde bulundurulmaktadır.

Tezimizde sayısal mimarlıkta biçim üzerine çalışılmasının pek çok nedeni bulunmaktadır. Öncelikle, mimarlık alanında gelişim, üç boyutlu modelleme ve zihinde canlandırmaya dayalı yeni yöntemler ve tasarım teknikleri üzerinden kavranabilmektedir. Bu yöntemlerin gelişimi yaratma, algılama, anlatma ve mimari biçimi oluşturma yeteneklerimizi arttırmaktadır. İkinci olarak, bilgisayar teknolojisinin mimarlıktaki rolü büyük önem kazanmakta ve fiziksel üretime/inşaya farklı bir yaklaşım oluşturmada öncülük etmektedir; bu nedenle bu bağlamda çalışma, teknoloji ile üretim arasındaki ilişkiyi yeniden şekillendirmektedir. Son olarak, her şeyin üzerinde, sayısal tasarım işlemlerini tanımlamak, tasarımlama ve uygulama arasındaki uçurum nedeniyle bazı tasarımcılar, mühendisler ve hatta eğitimli mimarlar için hala bir şekilde belirsizlik taşımaktadır. Bu nedenle, tez çalışmamız, sayısal biçimin tasarımı ile uygulaması arasındaki uçurumu azaltmaya yönelik olarak ilk aşamadan uygulama aşamasının sonuna kadar tüm aşamaları düzenli bir şekilde açığa çıkartmaktadır.

Bu araştırmada, düşünceden başlamak üzere uygulamaya kadar sayısal teknolojilerin teknikleri kullanılarak, mimari biçime ait işlemlerin anlaşılması amaçlanmaktadır. Örnek olarak; mimarlıkta biçimi geliştirmeye yönelik çalışan çağdaş mimarların yeni düşünceleri üzerine çalışma, biçimi ve her tür karmaşık biçimin inşa edilmesini mümkün kılan sayısal mimarlığın yardımını net olarak tanımlayacaktır. Böylece; araştırmamız, her tür sayısal biçimin yaratılmasında kullanılan araç ve yöntemlerin anlatılmasıyla, aynı zamanda biçimin inşa edilmesini mümkün kılan sayısal üretim işlemlerinin özetlenmesiyle sona erecektir.

Tezimiz, farklı bakış açıları bağlamında biçim üzerinde yoğunlaşmaktadır; ilki mimari biçimin önemi ve temel elemanlarının çalışılmasıdır. İkinci olarak yeni kavramların, yöntemlerin ve tekniklerin mimarlık bağlamında anlaşılması çalışılacaktır. Üçüncü olarak; sayısal tasarım araçları tasarım ve uygulama bağlamında sınıflandırılacaktır. Daha sonra sayısal uygulama işlemi incelenecektir. Son olarak, farklı mimarlara ait yeni düşünce ve projeler incelenerek sayısal biçimin uygulanmasına ait bütünsel bir görüş elde edilmesi sağlanacaktır.

Anahtar kelimeler: CAD/CAM, sayısal mimarlık, sayısal biçim, mimarlıkta bilgisayar teknikleri, sayısal tasarım araçları, sayısal tasarım yöntemleri, sayısal zincir, “CNC” bilgisayar sayısal denetimi, “RP” hızlı prototipleştirme, sayısal üretim.

DEDICATION

To the memory of martyr Farag Omar Makhyoun (God mercifulness is upon him)

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LIST OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

The form in architecture is considered as one of the most notably issue among other architectural studies. Generally, as the form is covering every interior space, events, and activities to satisfy the human needs, many architects, theoreticians, and design professionals have been involved in the case of architectural form to improve the architectural practices. During the history of architecture the form has been improving at every stage of architectural history which means that the philosophies, architects and design professionals making their concepts according to the human needs at each period. Historically; it has been known that at every period in architecture the form had been affected by different parameters.

Today; we live in the 21st century that technology is a very important factor in architecture. A new type of architecture can be realized clearly by the change in concepts of the recently thoughts, which will be discussed in the chapter seven.

Today's digitally educated architects are equipped with software initially created for other purposes such as advanced aviation, animation and even shoe design. Powerful computers allow architects to visualize buildings of unprecedented complexity. It seems that Computer software helps architects envision and depict their ideas, control and simplify complex calculations, and test alternatives. In fact, the digital realm can administer, unify, and streamline the architectural process from conceptualization to construction. Therefore, the effects of the computer on architectural design are very significant due to the fact that the computer is presenting everywhere and at every part of our society and architecture. Additionally; computers can be linked with manufacturers' computers and fabricating equipments, so it can be now produce structures, surfaces and shapes that simply could not have be built before. As a result, computers have made many of today's large, truly innovative architectural projects buildable [1].

Since 1990, "Computer-aided Design (CAD)" has become a widely adapted tool in the field of architectural design. Developed till today, the advancement of computer technology has also brought into the approach of the "Computer-aided Manufacturing (CAM)". Due to the fast development of CAD/CAM, digital tools are now playing a more and more important role in the design process. Nowadays, uses of digital tools are no longer limited to "simple drafting or final presentation; they have become digital design tools that can assist the designer in his/her thinking process" (Chiu and Chiu, 2003). İn the context of digital technologies; Mitchell in his essay was mentioned that Since the emergence of digital tools in the design process, the forms and structuring methods of architectures have been liberated from the traditional geometric confines, which, in result, induced the emergence of a new style architecture – free-form architecture (Mitchell, 1998).

Freedom from the confines of forms and liberation from the limitations of spaces have been the ideals desired and pursued by many architects in the past. For an example; in order to create an illusion of space in his design, Gaudi spent tremendous time in crafting and sculpturing along with numerous numbers of drafting to achieve his ideal. Another project that is representative to the style of free-form at earlier times would be the Sydney Opera House (1957 – 1973) by John Uzon. However, as the technology of digital tools were not yet matured at the time, construction technologies alone were not able to construct a style that is full of energy, elegant, and free, as the architect envisioned. In result, the architect had to settle for a more traditional geometric structure. Until 1992, Frank Gehry utilized the technology of CAD/CAM and created a fish-design sculpture for the Olympic Games in Barcelona. The move started a digital tool revolution in the profession of architectural design. In recent years, many renowned architects, such as Gehry, Greg Lynn, Peter Eisenman, UN Studio, Asymtote, and many others have all adapted digital tools into their design process to create a world of space/form liberated Free-Form Architecture.

In another aspect, studies of computer aided design have gradually moved the focus to the production and effects of digital tools in respect to the designs. This type of digital design process, which utilizes the aides of digital tools, has touched off wide discussions on various subjects – Mitchell (1998) discusses the formation and creation of free-form structures from the aspect of shape grammar, while Chiu (2003) explores when and how to appropriately utilize various digital tools based on the digital design process. Moreover, since actual execution of construction for free-form structures is more complex and difficult than that of the traditional geometric structures, studies on fabrication became even more important (Kilian 2003; Kocaturk, Veltkamp et al. 2003). Kocaturk attempted to create a set of "arithmetic computer system data structure" to aid in solving the "construction execution" problems of complex forms. In addition, many hardware auxiliaries, such as rapid prototyping (RP) technology, computer numerical control (CNC) and 3D Scanner, have also been developed to satisfy the needs (Shih, 2003).

From all the above research literatures, it seems that at current time, Applications of digital tools in the design process have gradually changed the traditional design process and also affected the outcome of designs. In a digital design process, "the architect has a bigger space to create more liberated and freer forms of design through the aids of computer software; however, such designs also create higher complexity in the free-form geometry" (Mitchell, 1998). Thus, designing production and fabrication solutions of such forms becomes an important stage in the design process. Although it seems that such design process and the forms resulted will be different from that of the tradition methods, what then are the factors that bring about the changes, and what procedures or steps in the design process are actually changed? These factors can be further discussed through the process of an actual design project. Moreover; "Integrating computer-aided design with computer-aided fabrication and construction fundamentally redefines the relationship between designing and producing. It eliminates many geometric constraints imposed by traditional drawing and production processes— making complex curved shapes much easier to handle, and reducing dependence on standard, mass-produced components". [Marc Aurel Schnabel, 2003]

Form in digital architecture has been studied for several reasons. Firstly, the improvement in the field of architecture can be realized on the new methods and design techniques which based on the three dimensional modeling and visualization. Thus; the emerging of these methods expands our abilities to create, perceive, to express and compose architectural form. Seemingly; Dealing with free surfaces and sensual elements of the human body is one of the important additions of digital architecture which caused major shift in the world of architecture today. These additions required to enter technology-intensive in the field of architecture both in terms of the architectural design and production process of these entirely free-forms, so that the vacuum architectural unrestricted certain limits, which make it more flexible for most of the requirements for primary and secondary users vacuum. Secondly, the role of computer technology in architecture has gained a marked significance and led to a different approach to physical production and construction; so studying in this context would reconfigure the relationship between technology and production. Finally, above all, defining the processes of digital design is supposed to satisfy a need for some designers to realize the journey starting from design, ending with production.

Our dissertation is an attempt to show the concepts, the tools, the methods of digital architectural design and the digital fabrication procedures for form production, by making an analysis of built projects. It is aimed to understand the production of architectural form by using the techniques of digital technology starting from thoughts ending with production. Studying the recent thoughts of contemporary architects who take part in improvement of the form in architecture is supposed to guide us to the identification of form in digital architecture as well as the aid of digital technology for making any type of complicated form possible to be built. As a method of the study, a deep research made through the latest news takes place in the internet, the books focused to the theoretical basis of architectural design and production of form in architecture. A big file of information was re-organized to create knowledge of architectural design in the context of production of form as drawing and construction.

As the thesis focus on the form from different view of studies; the first one is studying the importance and basic elements of architectural form, secondly understanding the new methods and techniques of creating form, and finally the production process; all in the context of digital forms. Therefore; the following section examines the importance of form in architectural design in general through the history of architecture, then briefly comparing between the normal form and digital form in the context of their elements, principles and methods.

The thesis has been realized into eight chapters: Chapter one, gives an introduction to the thesis by generalizing the importance of the topic through a brief history, including the general characteristic of using technology in architecture. Additionally, this chapter describes the aims and scope of the research. Chapter two comprises a definition of the concept of architectural form and a discussion on the importance of form in architectural design. Moreover; understanding the relationship between form and CAD/CAAD through a historical overview to find out how CAD/CAAD technique has been introduced to the field of architecture. Chapter three, indicates the growth and transformation of new architecture which assimilated in the realistic of digital form, additionally; defining the computational concepts of digital architecture to find out the recently thoughts on today’s architecture. İn chapter four; the theories, methods and some new concepts of digital form such as folding, topology, digital morphogenesis and others all of which will be used as a theoretical outline for evaluating and practicing the types of digital form. Chapter five; is a classification of the types of digital tools which assimilated in the software (CAD/CAAD) and hardware (CAM) of digital architectural technologies that facilitating the process of designing and fabricating the form in digital architecture. In chapter six; the methods of digital fabrication were bieng presented by diagramming the main lines of digital fabrication process using rapid prototyping (RP) and computer numerical control (CNC) which are the physical creation of digital form. Chapter seven; is a briefly presentation of the digital design chain starting from analyzing the recently works of different architects which will sum up all the research results in practical figures. Chapter eight; comprises the conclusion which includes the main findings of the study.

The following section examines the importance of form in architectural design in general throught the history of architecture by making a comparsion between the conventional form and the free-form in the context of thier elements, principles and methods.

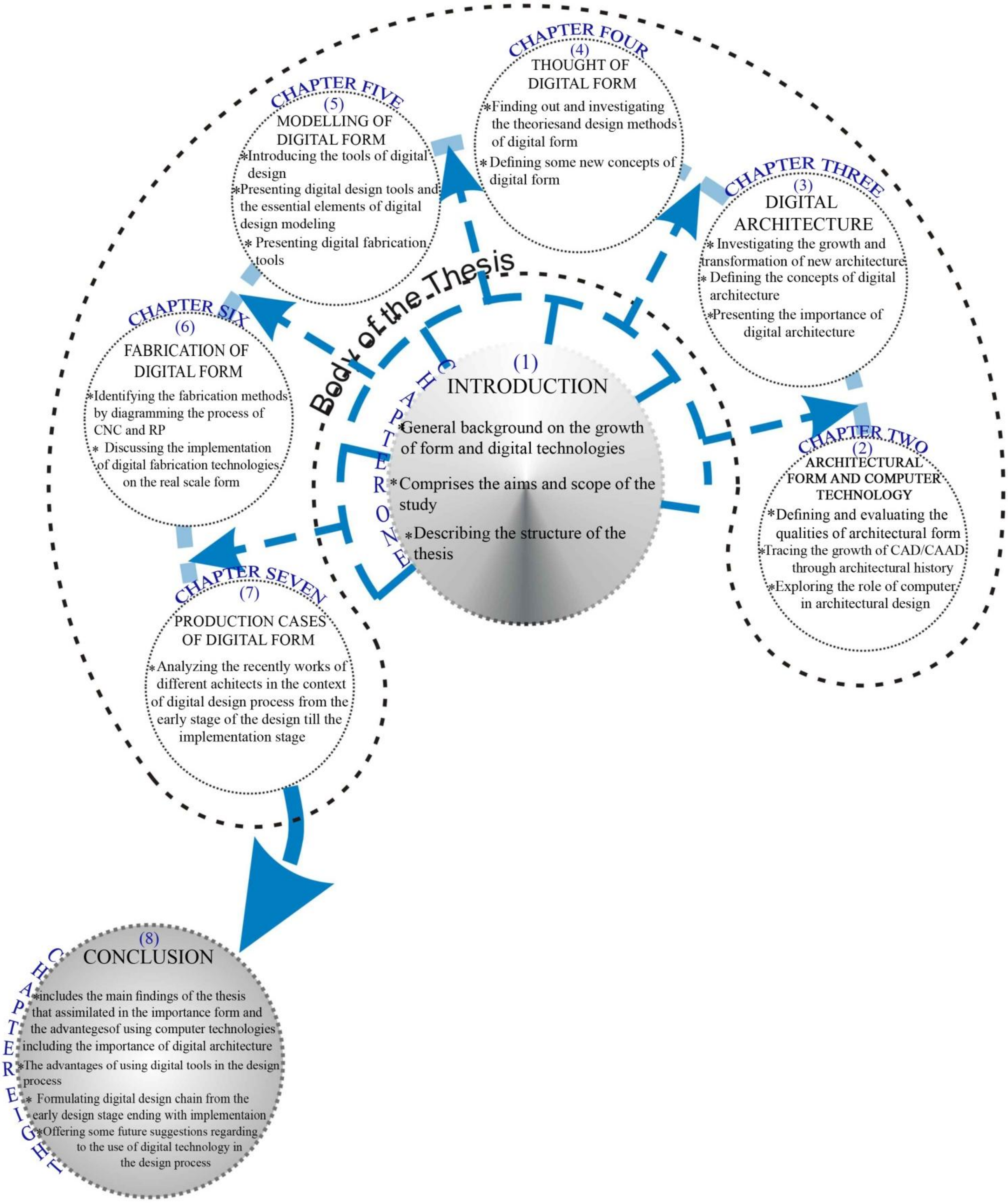


Figure 1: Structure of the Thesis

CHAPTER 2

ARCHITECTURAL FORM AND COMPUTER TECHNOLOGY

Through submitted prior interaction between the role of advanced technology and techniques of computer; architecture in general and the construction of special architectural form which is under study in this research has shown that there is significant progress in the field of engineering, construction and architectural merit attention today, which has helped to make the most complex forms that was difficult to establish is possible and easy to implement by such advanced technology.

Briefly, and through this chapter is to clarify the important development in the process of establishing the complex forms using these techniques. The study turning to the importance of architectural form in general and crystallize most important differences between traditional architectural form and complex forms through several modern standards; such as the basic elements of architectural form, the drawing methods and techniques, the materials used, methods of construction and several other criteria, which are duty bound to clarify the extent of development and additions in the field of engineering, architecture today and, in particular, supports the requirements and objectives of this research. All these parameters were derived through what has been reported about architectural form and the basics established by some analysts that the pioneers and in-depth analysis of form in architecture and have contributed to this progress, which we see today.

Since this progress can be sought from the relationship between the advanced computer software and architecture, the study turning to the importance of the computer and its role in architecture through a brief study that would link architectural form as a study and the possibilities provided by the entry of computer technology to architecture today. Through all the previous facts it’s become clear that there is a direct relationship between the growth of architectural form and computer technology and this what would be addressed in this chapter.

2.1. Form in Architecture

Form in general is an inclusive term that has several meaning. It may refer to an external appearance that can be recognized, it may also allude to a particular condition in which something acts or manifests itself. In art and design, it's often used the term to donate the formal structure of a work; the manner of arranging and coordinating the elements and parts of a composition so as to produce a coherent image. In this context, the form suggests reference to both internal structure and exterior outline and often includes a sense of three dimensional mass or volume. So the form in architecture can be defined as:

> "The shape and structure of something as distinguished from its substance or material. Also, the manner of arranging and coordinating the elements and parts of a composition so as to produce a coherent image"
> (CHING, 1996).

> "Architectural form is the point of contact between mass and space...architectural forms, materials, modulation of light and shade, color, all combine to inject a quality or spirit that articulates space. The quality of architecture will be determined by the skill of the designer in using and relating these elements, both in the interior spaces and in the spaces around building." (Edmund N.Bacon, *1974).*

Briefly; the form in architecture can be redefined as an outline that configuring the architectural space where the human activities and events are taking place. Also, the form has a huge impact on the architectural context becauce it connects the inside and outside. Therefore; the importance of form can be perceived from several points:

- The form is considered as the first physical element that we can see and perceive.
- It defines the space and the context where our activities are taking place.
- Also can be considered as the only element in architecture which connect the inside and outside.

- All the perceptual elements such as dimensions, scale, the quality of light, the quality and the substance of materials and other spatial boundaries are defined by the elements of form (CHING, 1996).

Form is considered to be one of the critical means of architecture that comprise a design vocabulary that is both elemental and timeless. “The analogy may be made that one must know and understand the alphabet before words can be formed and a vocabulary developed; one must understand the rules of grammar and syntax before sentences can be constructed; one must understand the principles of composition before essays, novel and the like can be written” (CHING, 1996). In a similar way, it might be appropriate to be able to recognize the basic elements and principles of the form in architecture and understand how they can be manipulated and organized in the development of a design concept, before addressing the main lines of the primary concepts in the design stage. Through the architectural history; several issues have been considered as the main topics in the architectural discussions which are activity, events, movement, space and form. In fact; the form in architecture is considered to cover all that issues as they can not be realized without the boundaries or the limitation of form.

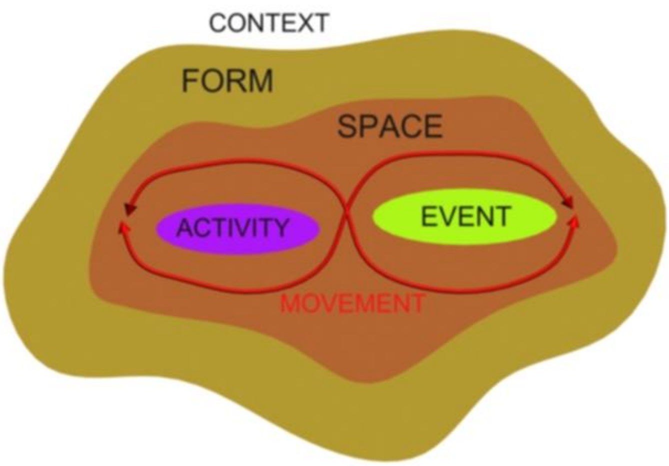


Figure 2: The status of form within architectural context

The study investigates the principles of form through the history of architecture, studying the main elements of different architectural styles to find out the difference between the common form and the digital form. The following tables illustrate the common points and importance of form accordding to different architectural thinkers and theorists who specially are concentrating on analyizing the form in architecture, like **“**FRANCIS D.K. CHING, ROGER H. CLARK, MICHAEL PAUSE, GREG LYNN, NOX, FRANK O. GEHRY,TOYO ITO**”** and other researchers by finalizing thier thoughts in particular order to find out the importance and qualification of form. These importance such as the elements of form, principles, style, realization, visualization, materials, design methods, and fabrication methods were briefly studied by making a comparsion between the conventional form and the free-form.

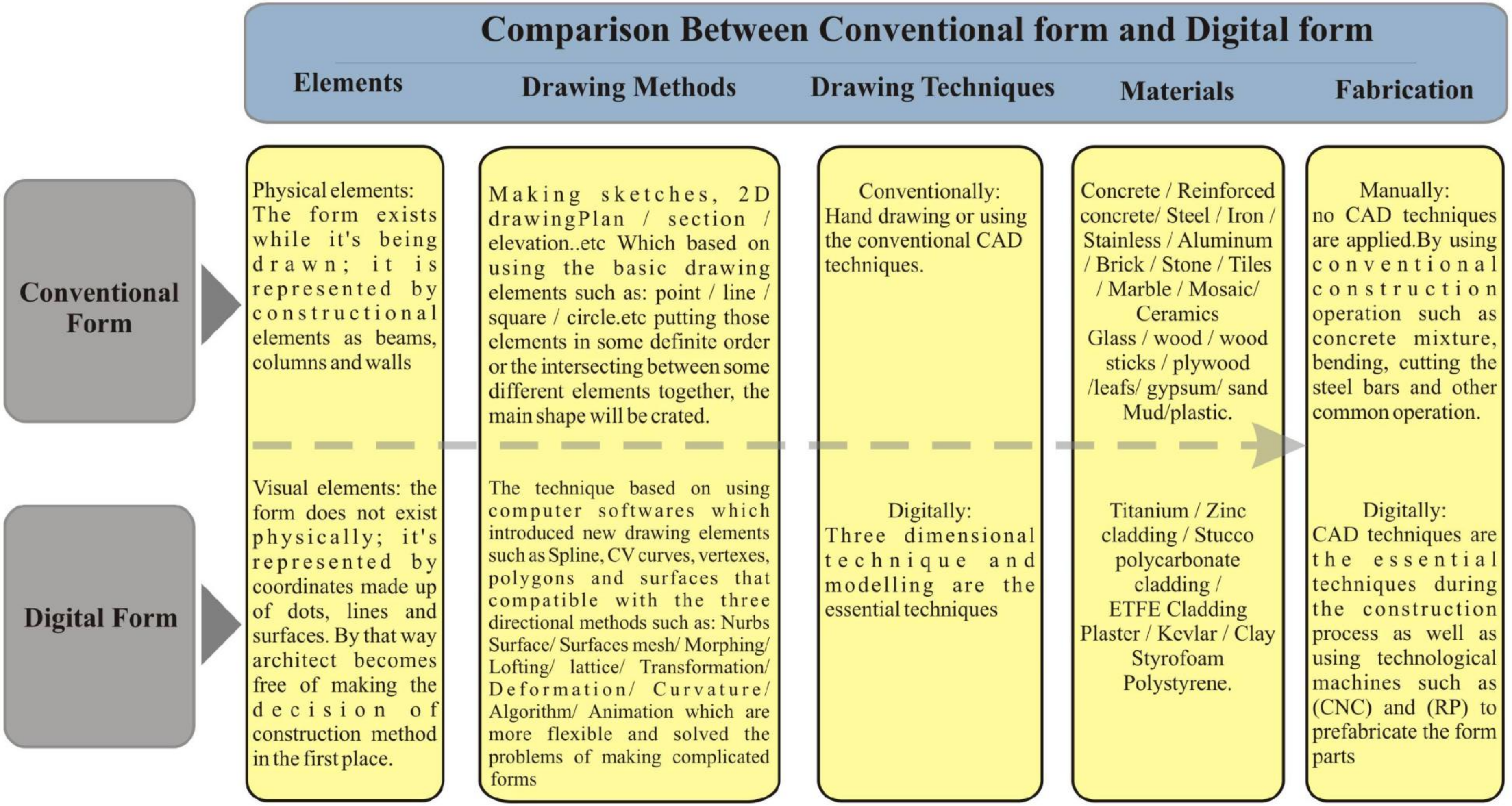


Figure 3: Comparison Between Conventional Form and Digital Form

That was a brief summary to introduce the importance of form in architecture in general and in the architectural design in particular. As the study focuses on the recently concepts of form in digital architecture, the term “digital” itself when connected to the term “architecture” may inflaming the curiosity of what kind of relationship between the architecture and digital!. In fact; the term digital may refers to the process of using the technological techniques which is based on some machines that working numerically such as the process of computer which is here considered as one of the research concerns. Therefore; the study investigates the relationship between the architecture and use of computer techniques which is refers to the term “digital”. So; it should be better to find out how the techniques of computer joined the field of architecture and in what way this technique has influenced the process of design in architecture. The digital techniques in the architectural design can be considered as the Computer-Aided (Architectural) Design (CAAD) which will be discussed at the following section and the Computer-aided Manufacturing (CAM) which will be discussed at the final chapter. The following section illustrates the growth of CAD/CAAD through the architectural history.

2.2. Growth of CAD/CAAD as Computer Technology

Computer-aided design (CAD) is the use of a wide range of computer based-tools that assist engineers and architects in their design activities. It involves both software and special-purpose hardware. CAD is something translated as “computer- assisted design”, “computer-aided drafting”, or a similar phrase related acronyms are CADD, which stands for “computer-aided design and drafting” and CAAD, for “computer-aided architectural design”. All these latter terms are essentially synonymous, and refer to the designing and technical drawing of various projects by use of computer rather than a traditional drawing board. The spectrum of architectural and engineering projects commonly created with computer-aided drafting is broad. And include architectural drafting, mechanical drafting, electrical drafting, and other forms of design communication. Today they constitute part of a broader definition of computer-aided design.

The first CAD (Computer-Aided Drafting or Design) tools were developed and used in the field of engineering, such as mechanical engineering or aerospace engineering.

In 1960, Ivan Sutherland used the TX-2 computer developed at MIT's Lincoln Laboratory (figure 2) to produce a project called "SKETCHPAD" (figure 3), "which is now considered as having been the first step towards the CAD industry" (Seung Yeon Choo, 2004). The concept of "SKETCHPAD", though written about forty years ago, which has been applied to many techniques, is still important today. It allowed an engineer to generate designs by sitting at an interactive graphics terminal, and manipulating objects displayed on the screen by use of a light-pen and a keyboard.

Figure 4: Ivan Sutherland at the console of the MIT TX-1demonstrating his PhD dissertation software *Sketchpad* in 1963.source MIT

(Source: http://accad.osu.edu/~waynec/history/lesson2.html)

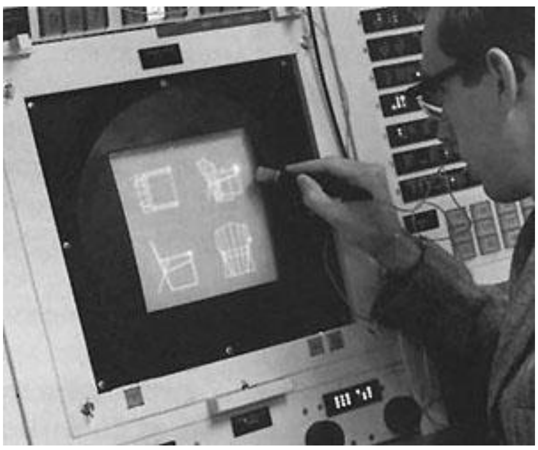


Figure 5: SKETCHPAD
(Source: http://accad.osu.edu/~waynec/history/lesson2.html)

Figure 6: The Process of Car modeling with SKETCHPAD, (Seung Yeon Choo, 2004).

The presentation of SKETCHPAD at the 1963 Spring Joint Computer Conference, and showings of a film on the system generated interest among many engineers in the potentials of computer-aided design. In the late 1960s, some of the architects saw the importance and the necessity of these tools for their work. However, these tools were not directed at the needs of designers and architects. They were isolated from architectural practice. In the 1970s, CAD was an electronic version of the drawing board and mostly 2D-orientated. This tool used simple “algorithms” to display patterns of lines in two dimensions. As the need for and the use of CAD have gradually grown, CAD tools have developed for architects and designers since 1980. In Germany between 1982 and 1983, it played an important role in both construction firms and design studios. There was a CAD-model called “2½D”, which generally referred to “the modeling of surfaces through x, y”, and other attribute values (Seung Yeon Choo, 2004).

Performance calculations, evaluation tools, and Presentation have also been improved. For example, wire frames and flat-shaded images are replaced by very realistic, interactive, virtual-reality models giving both clients as well as designers a much better understanding of the consequences of design decisions. Through the dazzling development of CAD systems between the 1980s and 1990s, current CAD systems, such as “all plans, ArchiCAD, AutoCAD/Architectural Desktop and Micro Station”, are not only building element based, but also offer the IFC exchange capability. Along with the development of CAD, CAAD was introduced in the 1950s to assist designers in assessing the optimization of their creations (Seung Yeon Choo, 2004). It was and is a process in which architectural designs are created using a computer.

The process of designing buildings continues to use habitual, manual methods, but at certain points along the design process quantities are measured manually and fed into computer programs that can analyze them. The results are then applied manually to the evolving design. An attempt at evolving a design in CAAD can be largely divided into two categories. One defines “grammar rules” about how design has to be and creates one or even a hundred solutions to choose from. Another approach is the “analysis of existing designs” to derive new solutions similar to the ones in the data base (Seung Yeon Choo, 2004). In short; the lately CAD techniques have been improved widely and assisted the designers and architects to manage, imagine, and build their ideas at the real world. By connecting the CAD technique with some fabrication machines that can transfer the drawing file format into physical form. This particularity has led any complicated form to be built easily. At the following part an illustration of the main points of CAD capabilities, tools, and methods that caused the wide improvement of analyzing and creating the concept of form in architecture.

Along with the growth of CAD systems during the last decade, the study found out several qualities of modern CAD during the long term of use whether in the design exploration, representation or construction process. The qualities can be summarized as follows:

- Re use of design components
- Ease of design modification and versioning
- Automatic generation of standard components of the design
- Simulation of designs without building a physical prototype
- Automated design of assemblies, which are collections of parts and/or other assemblies
- Output of engineering documentation, such as manufacturing drawings, and Bill of Materials
- Output of design directly to manufacturing facilities
- Output directly to a Rapid Prototyping or Rapid Manufacture Machine for industrial prototypes

By the gorwth of CAD some features have been resulted to assist the design practice and the production process which can be finalized as following:

- Wireframes
- Solid modeling
- Parametric design models
- Real-time process simulation
- Computer Numerically Controlled (CNC) load files (tool path instructions)
- Rapid prototyping

2.3 Role of Computer in Architectural Design

Although the computer is widely used in the design process. It is considered most of the time either as a rendering tool for presentation or as a fast drafting tool for technical drawings in two dimensions. Traditionally large sculptures or even car bodies were first made as small clay models, which were measured and enlarged. Now much of this work is done using computers employing software written for the automobile and aerospace industries. İn the context of using computer techniques during the design process Van Bruggen had givin an example on the work of Frank Gehry; for example "he uses aerospace software, but the starting point is still the physical models. For the Guggenheim Museum in Bilbao, paper models and clay models were first constructed, and then they were converted into usable geometrical information through a three-dimensional digital scanner" [Van Bruggen, 1997]. As Gribnau pointed out, "the digitizing process takes time and is open to interpretation faults, whereas using the CAD system in the early stages will prevent the digitized model from differing from the intention of the designer". Currently after creating a preliminary design on paper and in a scale model a designer typically translate his/her design to strict and exact representation of design in CAD programs, which demands a lot of time and effort.

As Gribnau stated, "if the computer is introduced at the conceptual phase several advantages can be gained. The designer can generate more alternatives of a design". On the other hand using computer supported modeling at the conceptual phase will support the integration with the lateral phases of the design process and offer many advantages including ease of transformation, archival, replication and distribution and make it possible to create forms without the limitation of real world material [Gribnau, 1999].

In his book “digital architecture”, James Steele identifies many types of “digital architecture and the role of computer techniques in the design process”, all with vastly different approaches to using the “new technology” and interestingly, all running concurrently, even though they seem to be different steps on an evolutionary scale of architecture (James Steele, 2001). One of these types is the most common – the “*use of the computer as a tool”* with which to simplify and speed up the drawing process. Here, it is difficult to see much difference from traditional design methods, the design process still takes place on paper and the computer is mainly used as a tool for assisting in drawing up the design. This method allows the architect to be more flexible in his design, as modifying drawings becomes less tedious, and complicated shapes and forms can be calculated with ease. Computer programs also allow these designers to virtually test their designs before construction starts.

One of the most notable firms associated with these method are Behnisch, Behnisch & Partner in Germany. As Stefan Behnisch says “We are old-fashioned when it comes to computers” (James Steele, 2001). Here, they use all the traditional design methods, heavily aided by physical models. The computer is merely used to take over repetitive drafting tasks and complicated calculations, as well as some technical explorations. Consequently, for example, the North German State Clearing Bank, Hannover, was designed entirely through sketching and work on models, but computer simulations showed structural inefficiencies in the design, and the suggested improvements were implemented into the final design.

Another prime example is the Polshek Partnership’s Rose Centre for Earth and Space in New York (Figures 7, 8)**,** a spherical planetarium that seems to effortlessly float within a glazed cube, bringing to mind drawings for the Newton Monument of old. Here, the design could not have been realized so elegantly without the use of computers to calculate the 5,599,663 lozenge-shapes acoustical pieces that make up the shell of the planetarium, or indeed the constantly changing spiral ramp surrounding it. The architects also relied on computer modeling to help the client visualize the complicated interior space.

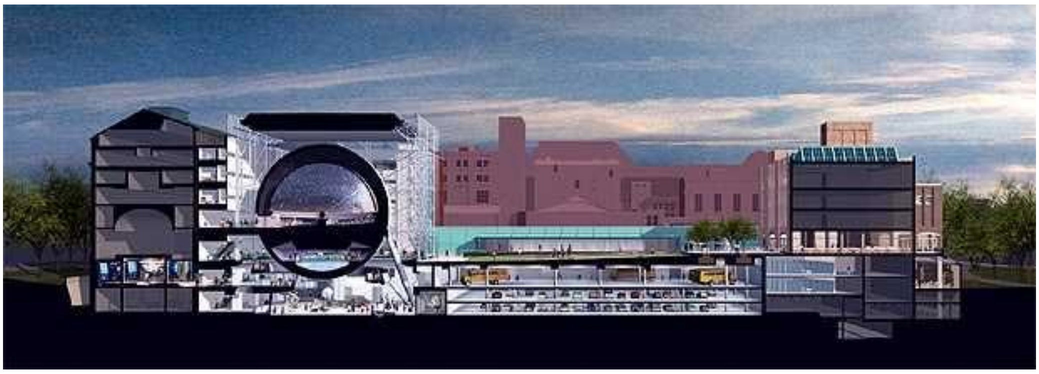


Figure 7: Section of Rose Centre for Earth and Space, New York. Arch: Polshek Partnership

(Source: http://members.lycos.co.uk/akarl/essays/digiarch.html)

Figure 8: View of Rose Centre for Earth and Space, New York. Arch: Polshek Partnership

(Source: http://members.lycos.co.uk/akarl/essays/digiarch.html)

Additionally; in this category, the famous architect for his hi-tech architecture, Sir Norman Foster. This firm is still deeply rooted in traditional design methods, while the computer features as a well-heeded advisor. Thus, the design for the Greater London Authority building by Foster and Partners was changed from its original spherical shape to its present form after computer testing showed this to achieve optimal environmental performance. Therefore, the improvement of current systems and computer techniques allow for the quick and interactive generation and development of objects, which make them sufficient for the early stages of the design process.

Recently; the emerging of digital tools which affect not only the way we produce drawings, but also the way we think about architecture. Three dimensional computation extends the architect's vision by permitting a wide range of experimentation of the forms seem impossible, improves the architectural language, changes the concepts of architectural debate, and provides various tools which opens various dimensions in the architectural design. “Using the digital drawing techniques in architecture presents a wide spectrum of approaches, from architects who incorporate the computer’s techniques into their working methods in a more efficient or exploratory way, to practices that are based on the belief that the computer will dramatically change the nature of architecture, in the terms of design process, as well as on the levels of organization and experience”.

“Architects, designers and engineers have been using computers for decades to increase productivity, to solve seemingly insoluble problems and for sophisticated presentations. It is only recently, however, that computers are being used not just as tools, but as creative devices capable of generating starting new design ideas and entirely unexpected forms for the built world” (Zellner, P, 1999).

Like MORPHOSIS; it’s well documented modes of workings in favor of a largely digital process of production. Mayne and his team currently build their drawings exclusively within the space of the computer. The architects at Morphosis employ the computer work continuously on a single object. Manipulating, rescaling, stretching, amending, subtracting and prying it apart until a design solution is reached. The process, according to Mayne:

> *“From the model produced on the first day, we just build, construct in one-to-one scale within the virtual space of the computer….no plan, no section, no elevation…it’s more like shaping clay. I hadn’t been interested in this technology until recently. The shift to computers in our office was made inevitable by the nature of practice today”.* He said (Zellner, P, 1999).

Also, for Morphosis the technique of computer has not only facilitated a new means of production but encouraged an examination of the very processes by which the studio generates its work and distributes project information, both internally and externally.

> Mayne says *"the computer has enabled the emergence of genuinely new morphologies for us, both in the translation of complex series of forms into a logical construction sequence, and as a means of looking at the results of our inquiry…understanding it in the terms of the program and assisting in its visualization…our client was able to see the physical environment as part of a creative, dynamic process of experimentation and inquisitiveness. They could participate vicariously in our investigations"* (Zellner, P, 1999).

Figure 9: Hypothekenbank, in Klagenfurt, Austria, morphosis, 1996-98.
(Source: http://www.arquitecturaviva.com/Noticias.asp.)

Figure 10: long section shows in detail how the complex program is incorporated into the building's elongated form by the use of computer software, (Zellner, P, 1999).

Another example that might clarify the role of computer and digital technology is the work of OOSTERHUIS Associates. He used the computer technique that facilitated the mathematical description of the complex forms geometries. As he calls "parametric modeling" the process he used at his design "*the saltwater pavilion"* was using "lines and surfaces and behind every line and surface is an algorithm that sets the parameters and interactive dimensions for its geometry". At the same time for the construction optimization; Oosterhuis developed a three-dimensional data base linked to a three-dimensional computer model for generating the relevant construction data for each building component- almost of which are unique (Zellner, P, 1999). Then the data were directly transferred to CNC-fabrication machines "will be explained at the chapter six" that cut, warped and sized the steel structural elements. Also here without digital technology and the ability of using the computer techniques such a project would have been impossible to be done.

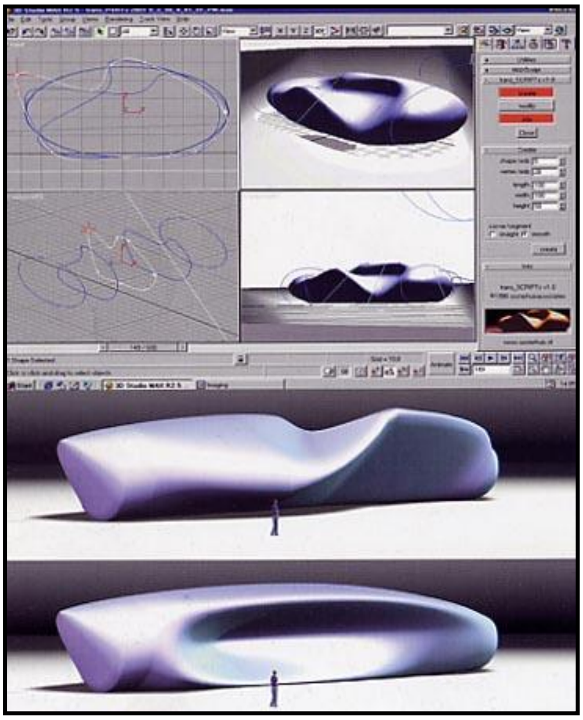


Figure 11: The method used in the project of TransPORTs2001, Oosterhuis.

(Source: http://w3.uniroma1.it/de_luca/caad_2003/lecture_tecniques-design/tech-des-mainframe2.htm)

Finally in this categories; Over the half decade Greg Lynn, principal of form, has revolutionized architectural thinking about movement, permanence, structure and the idea of static and anti-static. Because buildings have conventionally been defined by Cartesian fixed point coordinates and instituted through a state of inertia, Lynn argues that “an object or building should also be determined as a vectorial motion defined or directed along a path by allowing the form and structure to be designed within an unstable realm of variable, fluctuating dynamics and movements” (Embryo House, 1998) (figure 12). By that way, Lynn believes that:

> *“Architecture will move away from its inert logic of stationary relations into an operative rhythm of transmission and interaction”* (Zellner, P, 1999)

Basically; that kind of logic can be explained regarding to the architectural form as the forms or surfaces can be moved in space, and as they do so their shape changes according to a position within a gradient space. Thus, a topology or form duplicated but placed in a different context would behave differently depending on the influence and result in a unique and distinct configuration.

Briefly, Lynn sees the ability of computers to create the form by working with three properties of organization “time, topology, and parameters”. Time is a factor allowed by animation software which permits the possibility of key-framing and it allows objects to interact dynamically with one another. Topology is the area that allows surfaces to be formed using splines instead of points and lines. Splines are formed by the continuous sequence of vectors that define their shape; finally parameters provide the rules under which the object will deal with the passing of time and its changing topology. Parameters can be used to introduce a field with certain qualities to influence the form and generate an emergent new result. Thus; as the study of motion, Lynn sees “no other way forward than through the use of computer technology” (Greg Lynn, 1997). Therefore, the logic of Lynn required using special technique to approve his method and logic of the “animate forms” (Zellner, P, 1999). As a result of that; using the animation software was the solution of analyzing such logic in the architecture today.

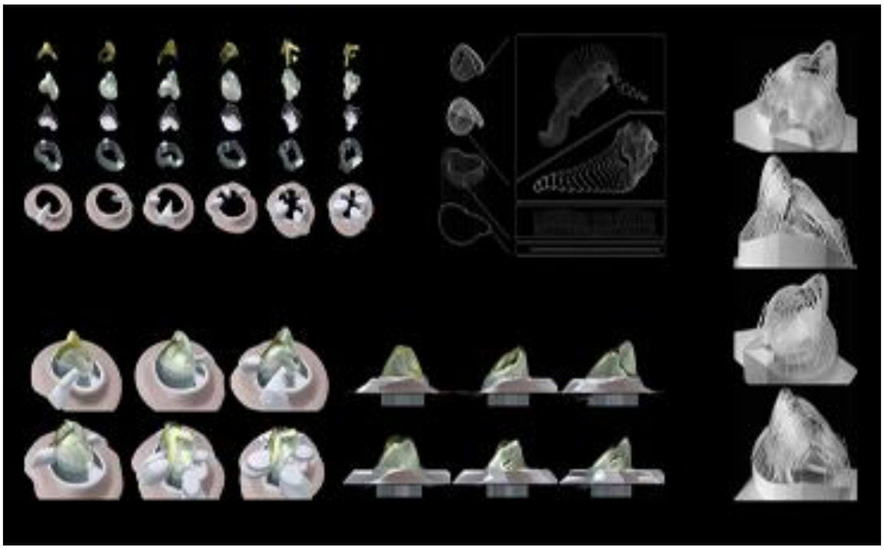


Figure 12: Greg Lynn's EMBRYO LOGIC HOUSE, USA
(Source:http://digilander.libero.it)

Consequently; according to the previous categories among the works of different architects that showed how the computer assists the assists the designer during the design process. Therefore; it can be said that using the computer techniques in architecture has shifted the way of thinking and experimenting in architecture into a new realm which made any type of form seem impossible to be done.

2.3.1. Advanteges of using Computer Technique

According to the above mentioned facts; it can be summarized the common advantages of using computer techniques during the whole design and construction process.

1- Three dimensional computation extends the architect's vision by permitting a wide range of experimentation of the forms seem impossible, improves the architectural language, changes the concepts of architectural debate, and provides various tools which opens various dimensions in the architectural design.
2- The computer and graphical softwares has become not only as a tool to manage or modify the design process but also the computer has become as a partner beside the designers and inventors.
3- Thinking digitally is a concept that helps to better understanding and connect the many attempts to establish the computer's role in architecture.

4- Opening the way for the inventors and creators of many opportunities to discover new techniques in architectural design beside of trying to validate architectural thinking in a different realm.
5- "Using the computer soft wares in the design process or visualizing the design's concept seems to be more like shaping clay" Morphosis said _ "for Morhposis the computer has not only facilitated a new means of production but encouraged an examination of the very process by which the studio generates its work and distributes project information, both internally and externally" (Peter Zellner, 1999). So that means working digitally has given more flexibility to the architectural design.
6- "The computer has enabled the emergence of genuinely new morphologies, both in the translation of complex series of forms into a logical construction sequence, and as a means of looking at the results of exploration" Mayne said (Peter Zellner, 1999).
7- Using digital techniques enabled the ability of facilitating the mathematical description of the complex forms geometries, also the optimization of the construction process.
8- "The discovery of animation techniques has brought the solution of moving the architecture away from its inert logic of stationary relations into an operative rhythm of transmission and interaction" (Greg Lynn, 1998).
9- It can be said that using the computer techniques in architecture has shifted the way of thinking and experimenting the architecture into a new realm which made any type of forms seem impossible to be done.

2.3.2. Computers in the field of architecture

The development of computer and CAD systems brought several choices in which program or software can be used through the design process. Particularly; in architecture the designer today has many choices to manipulate his work due to the diversity of CAD software that increased the qualities of invention in architectural design. Thus; there are many areas of computing in the field of architecture. Larry Sass has categorized the usage of computer in architecture into several stages. The following table comprises the use of computer in architecture.

Computers in the field of architecture	
Manipulation and presentation Programs	• Photoshop • Paint Programs
Generative Design Systems	• Genetic Algorithms • Shape Grammars
Digital Fabrication	• Rapid Prototyping • CAD / CAM
Design Process	• Modeling • Animation • Virtual Reality • VRML "Virtual reality modeling language" • Rendering

Table 1: The usage of Computer in Architecture, (Larry Sass, 2005).

The connection between CAD techniques and construction process is one of the most notable results among all the architectural improvements that have been done at the 21st century which solved the suspense of producing any type of forms that was impossible to build. Consequently; it can be said that the entrance of digital thoughts into the world of architecture has changed the way we perceive the form in architecture. Not only the form has been influenced by the digital technology, but also the architectural spaces and environment have been improved by this technology. Thus; understanding the methods, techniques and new thoughts of digital architecture would clarify and support the objectives of the study. The next chapter will introduce the general concepts of digital architecture and some related topics that have been discussed among the researchers, philosophers, and architectural designers.

CHAPTER 3

DIGITAL ARCHITECTURE

3.1 . Growth of Digital Architecture

In the past, while acknowledging the ingenuity and supreme aesthetics of digitally-developed projects by protagonists such as Frazer and Chu, their designers have been permissively as being removed from the reality of construction – the proposals, while intellectually stimulating and without a doubt deserving a place in the hall-of-fame of contemporary architecture, were considered unbuildable and therefore unrealistic. It is only in the past few years that this perception has been changed, most notably through an exhibition at the Deutsches Architektur Museum (German Museum of Architecture) in Frankfurt in 2001. Entitled “digital | real – blobmeister, first built projects” it showcased a collection of realized experimental “digital” projects by “blobmeister”. The term blobmeister was first used by Los Angeles architect Wes Jones to describe the digital architects who “use software the way modernists used structure: as a springboard for form” (Peter Cachola Schmal, 2002)

Although; in a less than positive way, referring to what he regards as unstructured “blob-like” designs, this exhibition turned out to be an important event, as it firmly placed digital architecture in the realm of reality, proving that it can not only be built, but successfully so. The exhibition featured varied built projects ranging from subway stations to churches and a garbage transfer station, designed by leading figures in the digital movement, such as Kas Oosterhuis, Gregg Lynn and Bernhard Franken, most of who also hold teaching posts worldwide. The garbage transfer station in Elhorst in the Netherlands designed by Kas Oosterhuis (Figure13) as early as 1995 was initially designed as a floating three dimensional body, “entirely conceived in digital space by 3D modeling and subsequent Boolean operations” (Kas Oosterhuis, 2002). This body was then juxtaposed onto the local context, i.e. the landscape and immediate environment, at which point the two were integrated as one visually, in order to follow the brief which called for subtlety in the positioning of the station.

Figure 13: Garbage transfer station, the Netherlands. Arch: Kas Oosterhuis
(Source: http://members.lycos.co.uk/akarl/essays/digiarch.html)

This project is one of the first fully digitalized buildings realized worldwide; after the modeling was done in Design CAD, it was up to the conventional AutoCAD package to produce the working drawings. Surprisingly, part of the brief was to ensure flexibility in the function of the building as it will possibly only function as such for fifteen years, after which the client wants to turn it into a concert hall or similar.

Another, very high profile and literal piece of blob-architecture is Jakob and MacFarlane's Georges Restaurant (figure14) on the top floor of the Centre Pompidou in Paris which was commissioned as part of the general refurbishment of the Centre. Here the architects, aware of the implications of changing such a renowned structure, decided to work with the existing grid, and alter the nature of the floor space by allowing aluminum "pockets" to deform it. These pockets were first sketched freehand and then optimized digitally (figure15), using a skeletal aluminum structure enclosed in aluminum sheeting. The software, Cap-sad, made it possible to reduce the amount of material, calculate the type of forces acting on the structures and then highlight possible problem zones. As a result, the architects were able to maintain the lightness of the original design without compromising the structural integrity of the restaurant.

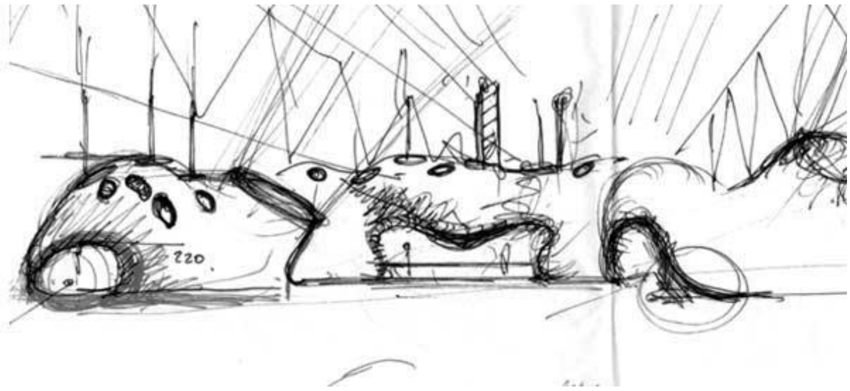


Figure 14: The freehand sketched of aluminum pockets
(Source: http://members.lycos.co.uk/akarl/essays/digiarch.html)

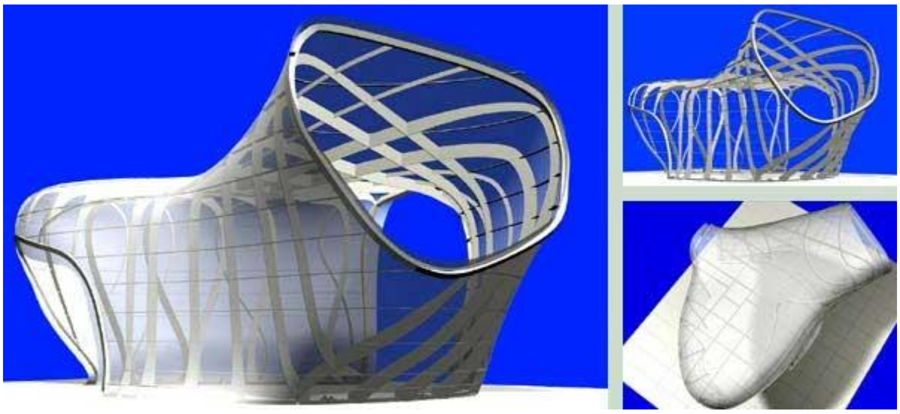


Figure 15: Georges Restaurant, Paris. Arch: Jakob and MacFarlane
(Source: http://members.lycos.co.uk/akarl/essays/digiarch.html)

A pure showpiece in how digital architecture can facilitate team work comes with the New York Presbyterian Church (figure16), a project undertaken by Michael McInturf Architects, Lynn-FORM and Garofalo Architects, all of which are based in different cities. The ability to exchange project information and expertise promptly by electronic means allowed these practices to undertake a massive project they could not have mastered individually. The church is housed within a disused 1930s factory building and hosts a variety of spaces, starting with the actual church space which seats 2500 people, as well as 80 classrooms for schools and community groups and a multitude of other spaces. The project was originally modeled using animation software, in order to create 3D core volumes that relate to one another. This virtual model could easily be modified during the design process and the results tested instantaneously by means of a simulated walkthrough. Once the design was laid down, different software allowed its construction, using Micro-station CAD to facilitate the calculation of structural conditions and other elements. The result is a well conceived building which adds to the original factory building and gives a much needed focus to the neighborhood.

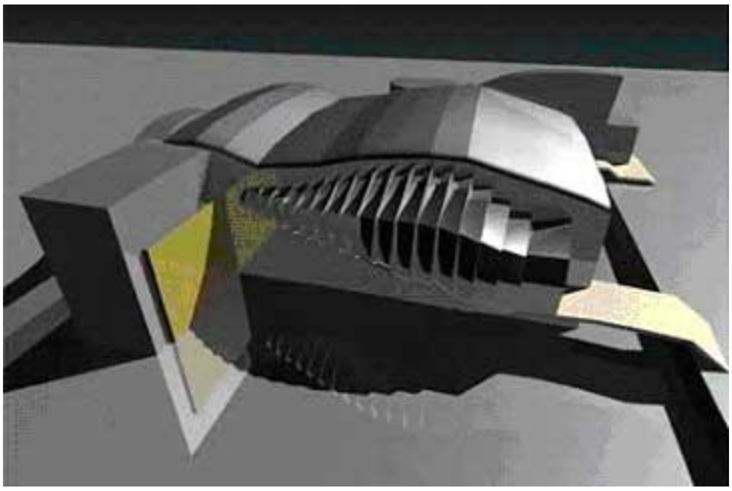


Figure 16: New York Presbyterian Church, New York. Arch: Michael McInturf Architects, Lynn FORM and Garofalo Architects (Source: http://members.lycos.co.uk/akarl/essays/digiarch.html)

Bernhard Franken, one of the leading blobmeisters designed his first built project, the BMW Groups Pavilion for IAA 2001 (Figure.17) in partnership with AAB Architekten. Franken says of his design that “we wanted to accelerate the space around the cars to such a degree as to produce the sensation of driving. To achieve this goal we chose to utilize the tool of the Doppler Effect.” (Bernhard Franken, 2002). In order to achieve this illusion, Franken’s team virtually coupled a BMW 7-series model with a force field and let it drive through a matrix of parallel lines. The arbitrary patterns produced by the lines in motion were then investigated and modified to produce the design. The final scheme was manufactured by developing a system of computer guided CNC torch-cut hollow profiles, a method where the price is dependant on weight, not the repetition of form, allowing the design to be undulating throughout. This means that Franken’s pavilion is, in fact, blob-architecture in its purest form, as it was constructed purely by digital processes.

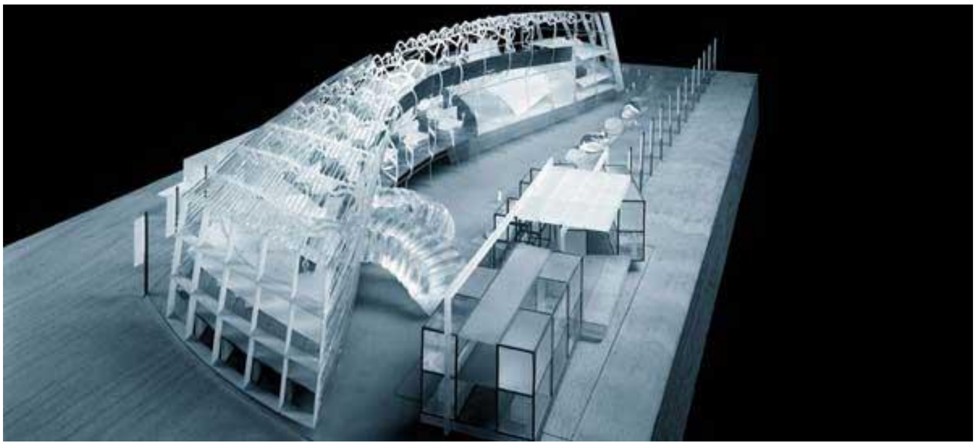


Figure 17: BMW Groups Pavilion for IAA 2001 Arch: Bernhard Franken with AAB Architekten

(Source: http://members.lycos.co.uk/akarl/essays/digiarch.html)

An essential part of the exhibition catalogue was the explanatory essays by pioneers such as Peter Zellner and Marcos Novak, who recounted their thoughts, theories and stories of the way of the blob. In his essay entitled "New Subjectivity: Architecture between Communication and Information", Antonio Saggio explains why the public will react positively to the new "blob-architecture". In his opinion, the modern movement removed the symbolic, communicative function of architecture; its buildings "could only communicate (their) function in tautological terms" (Antonio Saggio, 2002), making them abstract works of art. In today's society, narration and symbolism are becoming increasingly important, we are constantly surrounded by strong media influences, communication and information is essentially important. Architecture follows this trend, with more demand for "expressive" designs, such as the Guggenheim Museum in Bilbao or Libeskind's Jewish Museum in Berlin. The new forms offered by the blobmeisters will be able to satisfy this demand effortlessly, as well as delivering the innovative image sought by many clients. Peter Zellner agrees wholeheartedly, "intimating that the time is right for architectural improvement" [2].

3.2. Main Concepts in Digital Architecture

Basically, Hearing the term "digital" from the first step may clarify that there is a relationship related to the computer process. It could be seen that among the thoughts of today's architects and designers the process of architectural design is clearly depending on the use of computer techniques whether in creating the primary concepts or at the construction process.

The new digital approaches to architectural design as discussed in Kolarevic's assay "Designing and Manufacturing in the digital Age" (Branko Kolarevic, 2000) are based on computational concepts. The following table presents the recently concepts of digital architecture that have been discussed by Branko Kolarevic (2000) and Marc Aurel Schnabel (2003).

Concepts of Digital Architecture	
• Topological space →	Topological architectures
• Isomorphic surfaces →	Isomorphic architectures
• Motion kinematics & dynamics →	Animate architectures
• key shape animation →	Metamorphic architectures
• Parametric design →	Parametric architectures
• Genetic algorithms →	Evolutionary architectures
• Virtual Environments	

Table 2: The Concepts of Digital Architecture, (Marc Aurel Schnabel, 2003)

Digital architecture, in particular, refers to "the computationally based processes of form origination and transformations". [Marc Aurel Schnabel, 2003]. The study briefly explaining the previous concepts of digital architecture that would open-up the general idea and roots of the digital thoughts in today's architecture.

3.2.1. Topological Architectures

In his essay "architectural curvilinearity" Greg Lynn offers examples of new approaches to design that move away from the deconstructivism's "logic of conflict and contradiction" to develop a "more fluid logic of connectivity." This is demonstrated through folding that departs from Euclidean geometry of discrete volumes, and employs topological, "rubber-sheet" geometry of continuous curves and surfaces (Greg Lynn, 1993).

In the context of topological space, Branko Kolarevic argued that the "geometry is represented by parametric functions, which describe a range of possibilities". The continuous, highly curvilinear surfaces are mathematically described as "NURBS – Non-Uniform Rational B-Splines". What makes NURBS curves and surfaces particularly appealing is the ability to easily control their shape by manipulating the control points, weights, and knots. "NURBS make the heterogeneous and coherent forms of the topological space computationally possible" (Branko Kolarevic, 2000).

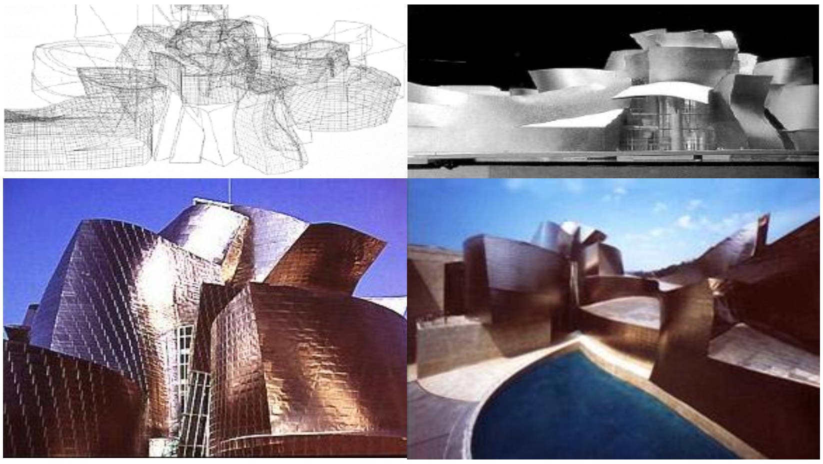


Figure 18: Guggenheim Bilbao by Frank Gehry, (Kolarevic, 2000).

3.2.2.Isomorphic Architectures

Isomorphic architecture is based on "***isomorphic polysurface*"** or what in special effects and animation industries commonly refer to as "*meta-clay, meta-ball* or *blob models*" (Branko Kolarevic, 2000). It was originally developed for the study of complex molecules. Popularized by Greg Lynn, it provides an alternative to the Platonic solids and Cartesian space which traditional architecture is based on. "Blobs or metaballs, or isomorphic surfaces, are amorphous objects constructed as composite assemblages of mutually inflecting parametric objects with internal forces of mass and attraction. They exercise fields or regions of influence, which could be additive or subtractive". The geometry is constructed by computing a surface at which the composite field has the same intensity "isomorphic surfaces". These open up another formal universe where forms may undergo variations giving rise to new possibilities. Objects interact with each other instead of just occupying space; they become connected through a logic where the whole is always open to variation as new blobs (fields of influence) are added or new relations made, creating new possibilities. The surface boundary of the whole (the isomorphic surface) shifts or moves as fields of influence vary in their location and intensity. In that way, objects begin to operate in a dynamic rather than a static geography (Branko Kolarevic, 2000). The BMW-Pavilion by Bernrard Franken and the Korean presbyterian church by Greg Lynn in collaboration with Micheal Mcluturf and Douglas Garofalo are an examples of isomorphic architecture (figures 19, 20). The project of Korean church is "the first of its kind to use and popularize the concept of the blob" (Brussels, 1998).

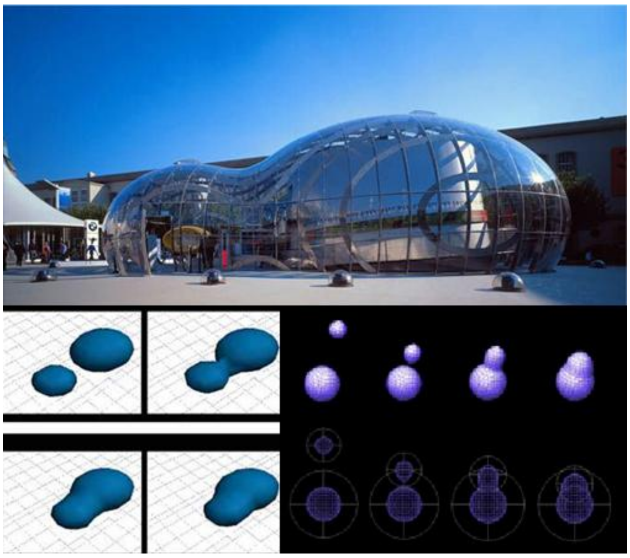


Figure 19: BMW-Pavilion by B. Franken, (Kolarevic, 2000).

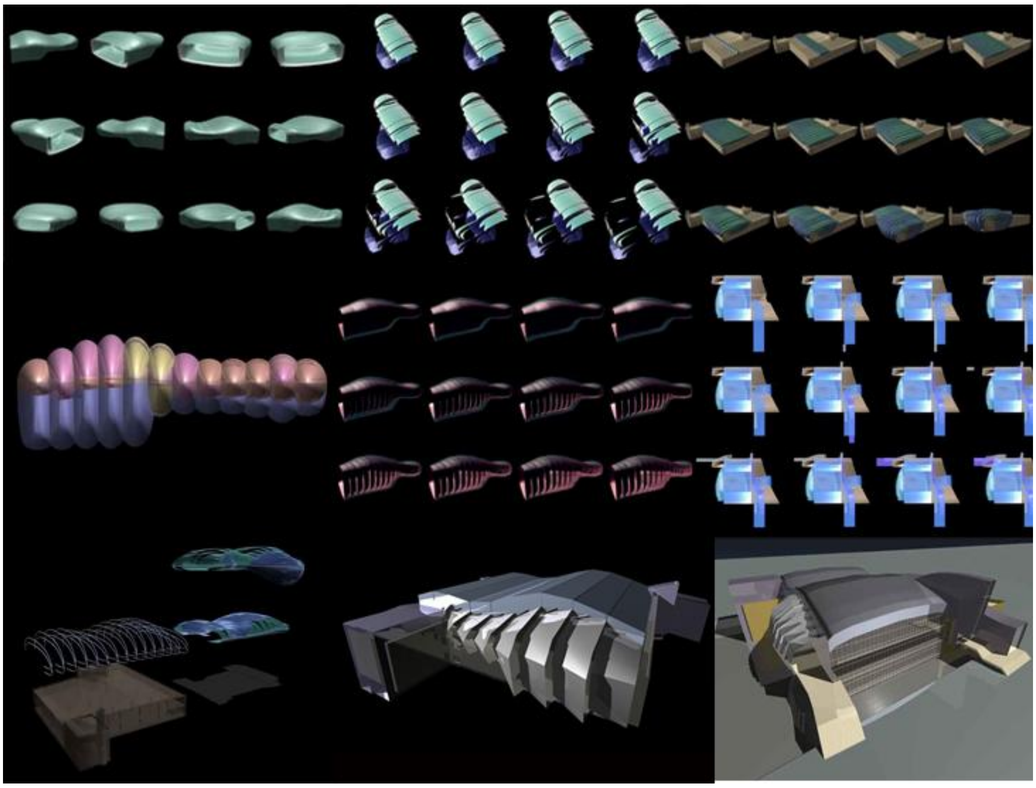


Figure 20: The collaborative project of Korean presbyterian church by Greg Lynn, M. Mcluturf and D. Garofalo
(Source: http://courses.arch.hku.hk)

3.2.3. Animate Architectures

In animate architectures, design, as described by Lynn (1998), "is defined by the co-presence of motion and force at the moment of formal conception." Force, as an initial condition, becomes "the cause of both motion and particular inflections of a form." According to Lynn, "while motion implies movement and action, animation implies evolution of a form and its shaping forces." In his projects, Lynn utilizes an entire repertoire of motion-based modeling techniques, such as key-frame animation, forward and inverse kinematics, dynamics (force fields) and particle emission to generate the initial architectural form (Greg Lynn, 1998).

Kinematics are used in their true mechanical meaning to study the motion of an object or a hierarchical system of objects without consideration given to its mass or the forces acting on it. As motion is applied, transformation are propagated downward the hierarchy in forward kinematics, and upward through hierarchy in inverse kinematics. In the House Prototype in Long Island by Greg Lynn, the “skeletons with a global envelope are deformed using inverse kinematics under the influence of various site induced forces” (Kolarevic, 2000).

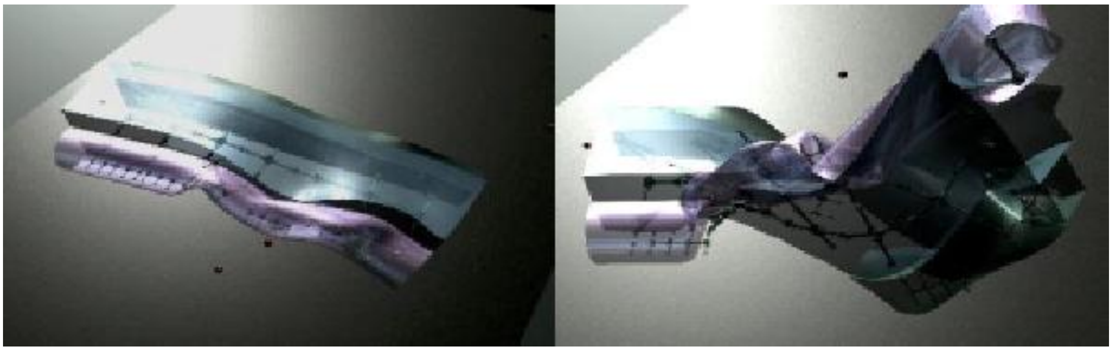


Figure 21: Kinematics, House in Long island by Greg Lynn, (Kolarevic, 2000).

Dynamic simulations take into consideration the effects of forces on the motion of an object or a system of objects, especially of forces that do not originate within the system itself. Physical properties of objects, such as “mass (density), elasticity, static and kinetic friction (or roughness), are defined. Forces of gravity, wind, or vortex are applied, collision detection and obstacles (deflectors) are specified, and dynamic simulation computed” (Marc Aurel Schnabel, 2003).

Figure 22: Dynamic simulations at Port Authority Bus Terminal in NY by Greg Lynn, (Kolarevic, 2000).

3.2.4. Metamorphic architectures

Metamorphic generation of form includes several techniques such as “key-shape animation, deformations of the modeling space around the model using a bounding box (lattice deformation), a spline curve, or one of the coordinate system axis or planes, and path animation, which deforms an object as it moves along a selected path”. In key-shape animation, the changes in geometry are recorded as key-frames (key-shapes) and the software then computing the in-between states. In deformations of the modeling space, “object shapes conform to the changes in geometry of the modeling space” (Marc Aurel Schnabel, 2003).

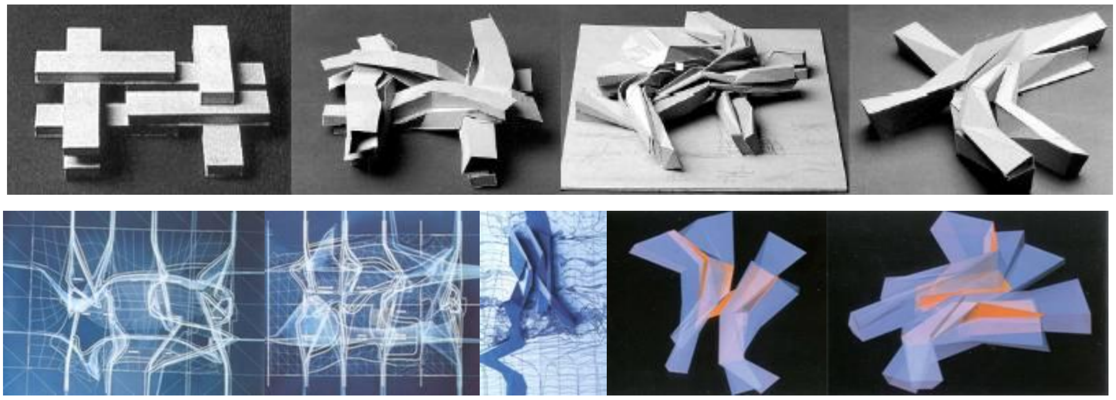


Figure 23: Offices of BFL Software ltd. by Peter Eisenman, (Kolarevic, 2000).

3.2.5. Parametric Architectures

In parametric architectures, it is the parameters of a particular design that are declared, not its shape. By assigning different values to the parameters, different objects or configurations can be created. Equations can be used to describe the relationships between objects, thus defining an associative geometry. The “constituent geometry that is mutually linked” (Burry, 1999). That way, interdependencies between objects can be established, and objects’ behavior under transformations defined. As observed by Burry, “the ability to define, determine and reconfigure geometrical relationships is of particular value.”

Parametric design often entails a procedural, algorithmic description of geometry. In this “algorithmic spectaculars”, i.e., algorithmic explorations of “tectonic production” using mathematical software, architects can construct mathematical models and generative procedures that are constrained by numerous variables initially unrelated to any pragmatic concerns (figure 24). “Each variable or process is a ‘slot’ into which an external influence can be mapped, either statically or dynamically” (Marc Aurel Schnabel, 2003).

Figure 24: Algorithmic spectaculars by M Novak, (Kolarevic, 2000).

3.2.6. Evolutionary architectures

Evolutionary architectures propose the evolutionary model of nature as the generating process for architectural form. In this approach to design, according to John Frazer (1995), “architectural concepts are expressed as generative rules so that their evolution and development can be accelerated and tested by the use of computer models.” Various parameters are encoded into the “a string-like structure” and their values changed during the generative process. A number of similar forms, “pseudo-organisms,” (figure 25) are generated, which are then selected from the generated populations based on predefined “fitness” criteria. The selected “organisms,” and the corresponding parameter values, are then crossbred, with the accompanying “gene crossovers” and “mutations”, thus passing beneficial and survival enhancing traits to new generations. Optimum solutions are obtained by small incremental changes over several generations.

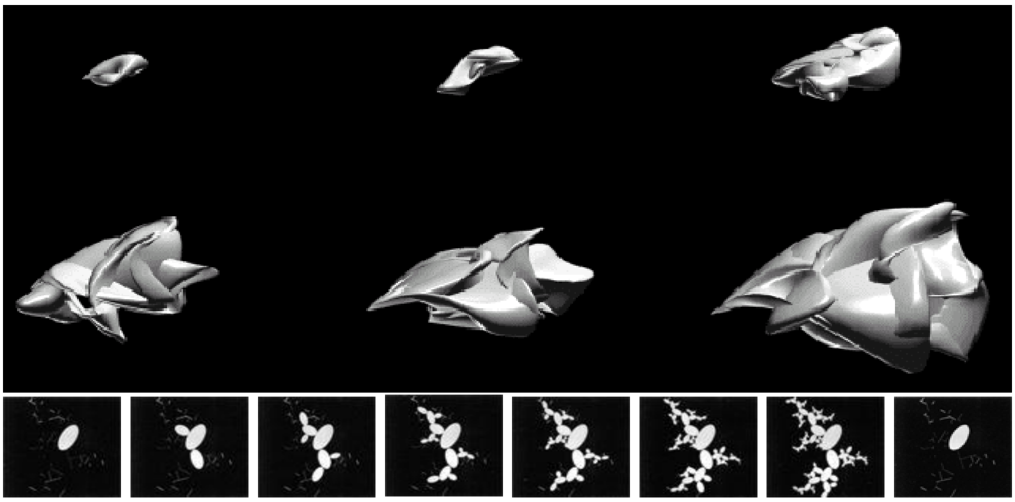


Figure 25: “pseudo-organisms” by J. Frazer, (Kolarevic, 2000).

What is common to all these approaches is an almost exclusive use of topological geometries, “Topology is the science of self-varying deformation,” observes (Brian Massumi, 1998). Topological space opens up a universe where essentially curvilinear forms are not stable but may undergo variations, giving rise to new possibilities, i.e., the emergent form. Designers can see forms as a result of reactions to a context of forces or actions, as demonstrated by Lynn’s work. There is, however, nothing automatic or deterministic in the definition of actions and reactions; they implicitly create fields of indetermination from which unexpected and genuinely new forms might emerge, unpredictable variations are generated from the built multiplicities.

Thus; as observed by McCullough the capacity of digital architectures to generate new designs is therefore “highly dependent on designer’s perceptual and cognitive abilities, as continuous, dynamic processes ground the emergent form, i.e., its discovery, in qualitative cognition”. Their generative role is accomplished through the designer’s simultaneous interpretation and manipulation of a computational construct (topological surface, isomorphic field, kinetic skeleton, field of forces, parametric model, genetic algorithm, etc.) in a complex discourse that is continuously reconstituting itself - a ‘self-reflexive’ discourse in which graphics actively shape the designer’s thinking process. It is precisely this ability of “finding a form” through dynamic, highly non-linear and indeterministic processes that gave the digital media a critical and generative capacity in design. Even though the technological context of design became thoroughly externalized, its arresting capacity remains internalized (McCullough, 1996).

3.2.7. Virtual Environments

Virtual Environments can be defined as the use of computer modeling and simulation to enable a person to interact with an artificial three-dimensional visual or other sensory environment. VR applications immerse the user in a computer-generated environment that simulates reality through the use of interactive devices, which send and receive information and are worn as goggles, headsets, gloves tracking devices, CAVES and other media (figure 26). Some simulation devices as categorized by Marc Aurel Schnabel (2003) are:

- Augmented Reality
- Head Set
- CAVE
- Workbench
- Illusion-hole

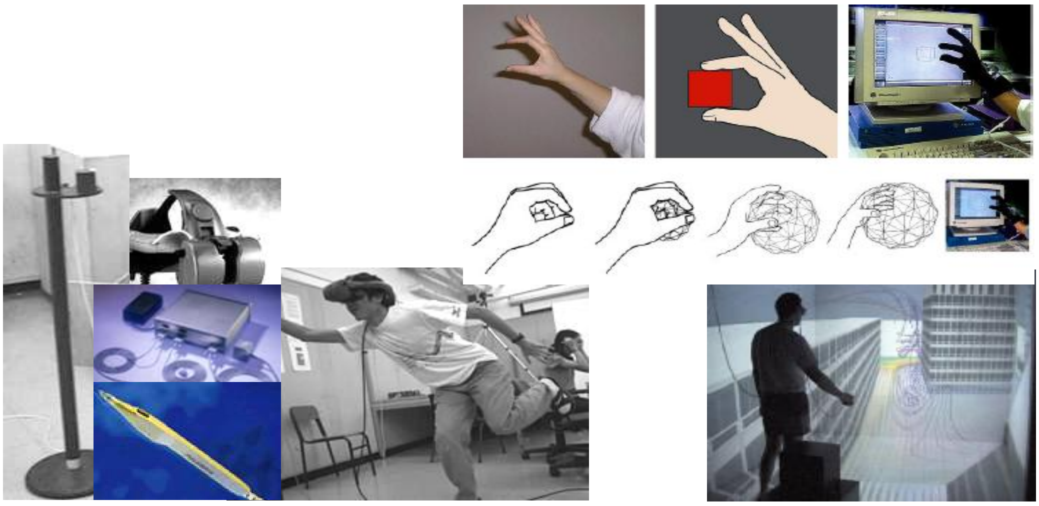


Figure 26: The simulation that enables a person to interact with an artificial three-dimensional visual or other sensory environment which called "Immersive VE", (Marc Aurel Schnabel, 2003).

3.3. Importance of Digital Architecture

In the early stages of its employment, architects approached computer technology as an assistance technique that would enhance architectural practice. "The role of computer technology in architecture has gained a marked significance and led to a different approach to physical production/construction" (Marc Aurel Schnabel, 2003). The scope has now been extended for architects to contemplate on the digital technology tools which would enhance their works and practical concepts.

The main focus in the development of digital tools for enhancing the practice of architecture has been the facility with which the various tasks involved have been represented, enabled or enhanced using computer technology. The digital representation of architectural entities and the digital manipulation of those entities have provided alternate means to produce architecture (construction). Drawing, modeling, performance simulation, design collaboration, construction management and building fabrication are now routinely performed using computer-based technology. This success has revealed the untapped potential of the computational representation of architecture.

Developments in digital technology based on the study of natural processes such as neural processing, genetic evolution and emergence now suggest that the elusive nature of creative architectural thought can be articulated enough to be applied in a technologically-mediated environment. Digital tools may finally disclose what other architectural tools have hitherto concealed – the architectonics of architecture. The future of digital tools rests on the extent to which architects can accept that exemplary architectural designs that can be created in a computer-mediated environment and that digital thinking is indeed architectural thinking.

The digital age has radically reconfigured the relationship between “conception and production”, creating a direct digital “link between what can be conceived and what can be built” through “file-to factory” processes of computer numerically controlled (CNC) fabrication (Branko Kolarevic, 2003). This new found ability to generate construction information directly from design information is what defines the most profound aspect of contemporary architecture. The close relationship that once existed between architecture and construction could potentially reemerge as an unintended but fortunate outcome of the new digital processes of production.

The digital generation of information to manufacture and construct buildings can render the present inefficient hierarchies of intermediation unnecessary. The 1st International Conference on Digital Architecture & Construction considers these facts in the meeting. “As architecture design and constructability becomes a direct function of computability, the question is what new instruments of practice are needed to take advantage of the opportunities opened up by the digital modes of production?” (A. Ali, 2006).

Particularly, in the context of the thesis issue, the development of architecture and digital techniques not only provides new production methods such as computer rendering and modeling, but also expands our abilities to create, to see, to express and compose architectural form. The emerging of digital architecture and its new way of dealing with architectural issues changing many aspects in today’s architecture. Through the previous section it can be realized that how the process of design have been improved and why so many architects attended to use the digital techniques for generating and improving their concepts. Obviously; it was only within the last few years that the advances in computer-aided design (CAD) and computer-aided manufacturing (CAM) technologies have started to have an impact on the design process and construction practices. They opened up new opportunities by allowing production and construction of very complex forms that were until recently very difficult and expensive to design, produce, and assemble using traditional construction technologies. Therefore; the supplementations of digital technology on the design process, design presentation and construction process have reduced the gaps of discussion between the designer and client, the architect and builders and so on.

Therefore; so many problems have been solved by the entrance of digital technology into the world of architecture. As indicated at the previous section some architects such as Frazer and Chu suffered from being unrealistic and some others had difficulties to express their ideas; but the entering of digital technology specifically into architectural design has solved all that problems.
As discussed before digital architecture is based on computer techniques and using the graphical software; it can be summarized that the most important advantages that have been gained from the entering of digital techniques into the world of architecture as following:

- The digital techniques have made possible new modes of expression.
- The use of computer has undoubtedly shortened planning-phases. Thus, building-costs can be reduced.
- New design ideas can be explored directly by manipulating three-dimensional objects or spaces, without translating them into two-dimensional drawings.
- An increased number of design alternatives can be generated.
- New types of materials have been discovered which facilitate the operation of construction and fabrication.

The following table describes some changes and improvements that have been done in architecture today which can be summarized according to some architects and theorists as following:

Types of computer techniques	Architects/Theorist
Conceptual initial, exploration of more dynamic and unpredictable forms	Peter Eisenman
Transformation of an idea into physical reality for achieving design goal	Frank Gehry
Standard tool which has replaced traditional design planning, tool for acoustic effects	Günter Behnisch
Using computational motion geometry and time-based dynamic-force simulations (animate design).	Gerg Lynn
Analysis of free form clay models	William J. Mitchell
Analysis of existing objects and exploration of objects involved	Mark Burry
Structural analysis	Nicholas Grimshaw
Expressing invisible environmental elements (wind, light, traffic noise) through media instruments. (Hypersurface system).	Toyo lto STEPHEN PERELLA dECOI
Liquidizing Form: Real-time form, lighting, sound changing through user action.	NOX

Table 3: The improvement on the design process based on using technology, (Seung Yeon Choo, 2004)

Briefly; the importance of digital architecture can be perceived from the integrating of computer-aided design with computer-aided fabrication and construction which fundamentally redefines the relationship between designing and producing in architecture. “Digital production and manufacturing processes demonstrate powerful tools, by which architects conceptualize the design process and controlling the operation of construction" (Mitchell, W. and M. McCullough. 1995).

CHAPTER FOUR

THINKING ON DIGITAL FORM

4.1. Theories of Digital Form

The entry of new techniques and digital technology into the world of architecture has shifted some theoretical bases in today's architecture specifically in the context of design process. In this section the study investigates several types of theories and methods as well as some new Vocabularies regarding to the form in digital architecture. Due to the diversity of the latest theories that have been discovered today which solved various architectural issues, the concentration of the study will be through the only types of theories that related to the issue of form in the digital edge.

Today's blurred relationships between things and unstable territories of cable cities, the concept of space changed into "time-space". Time-space is experiencing space in the context of event/activity. This new kind of space is related to the movement of the body, the real and the virtual and the heterogeneity of the environment. The main idea behind the digital form can be summarized as "an experimental investigation of topological geometries, rebating material investigation and kinematic sculpting of space". (Zellner, P. Hybrid Space: New Forms in Digital Architecture, Thames and Hudson Ltd., London, 1999, p. 8.). In other words, digital form is about operating on surfaces. Operative character of digital form creates its own concepts in the context of production like: transformation, hypersurface, folding, topology, digital morphogenesis, morphing and non- linear systems. Thus; the thesis will briefly illustrates the given theories and concepts supported by some known projects.

4.1.1. Theory of Transformation

Transformation can be defined as "the act of changing in form or shape or appearance" [3]. For instance; one certain shape or form might be changed into a new one according to some sequences of modifications. Those sequences can be defined as a particular order that affects the main elements of the original form (figures 27, 28). Briefly; the transformation can be done only on one certain object which means that it can not be transform two different objects into each other because such a case has other basics which called “Morphing”.

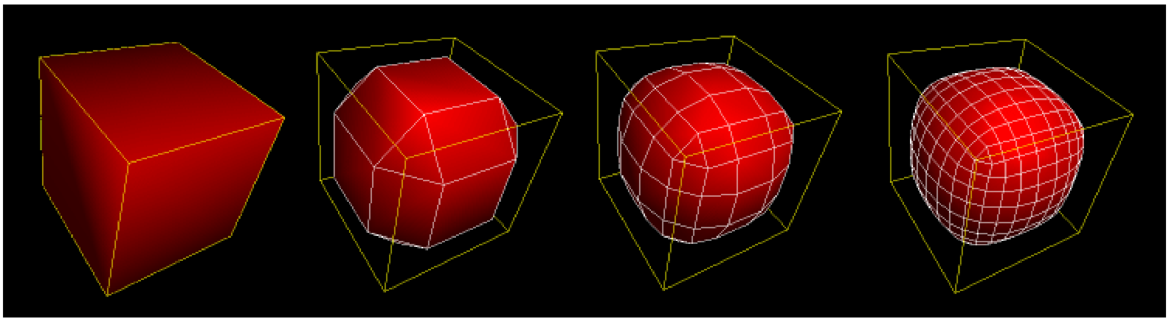


Figure 27: Some experiments done by using 3ds max to transforming basic Cube to be irregular form.

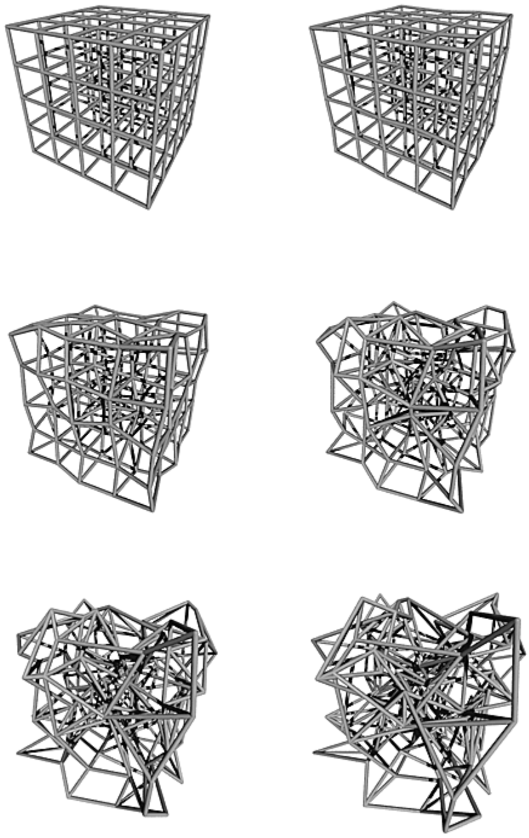


Figure 28: Transformation on wire framed box.

(Source: http://www.evolutionzone.com/hardwork/old_form/d3/grid.html)

To express the idea of transformation clearly; the study investigates an example of the young architects NOX one of the professional on digital modelling and computer-aided manufacturing. Their project of H2O expo which known as the “water pavilion” (1994-1997), located in Zeeland south-west of the Netherlands.

The building’s geometry is generated through interactive transformation. It starts with a simple tube made up of ellipses, which are rescaled according to the “internal programme, then deformed according to site influences, such as wind direction, sand dunes and flows of incoming visitors”. The entrance begins with a small ellipse on its vertical axis and ends, some 60 meters further on, with a larger ellipse on its horizontal axis. In between, the building twists and turns. Since the sections are continuous and floor blends into wall and wall into ceiling. “The visitors of the building must act like water to pass through the building”. The set of operations as follows: elliptical tube, scaling of tube according to programme, twisting according to exterior forces, insertion of ground level, deformation of ground surface (Lars Spuybroek, 2004)

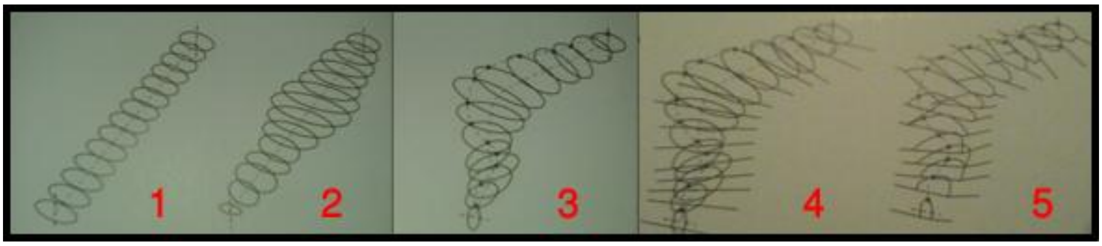


Figure 29: The transformation process of an ellipse into three dimensional form, (Lars Spuybroek, 2004).

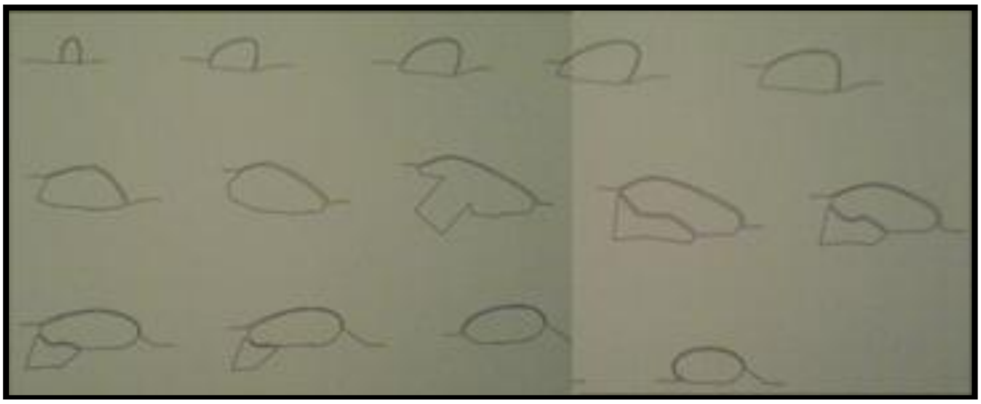


Figure 30: Transformation of the ellipses shape and the ground surface, (Lars Spuybroek, 2004)

Figure 31: The real structure of the water pavilion

(Source: http://www.noxarch.com/flash_content/flash_content.html)

Figure 32: The exterior surfaces of the main form.

(Source: http://www.noxarch.com/flash_content/flash_content.html)

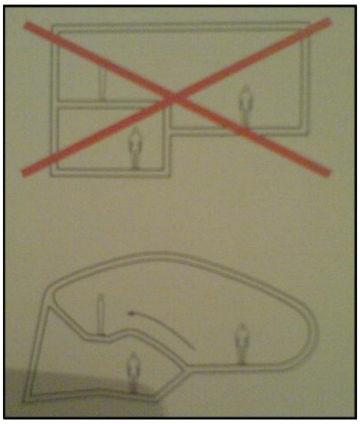


Figure 33: The logic of transformation on the interior surfaces, (Lars Spuybroek, 2004)

Another example; in Eisenman's early projects, transformation was a step-by-step procedure by which one element is substituted by another: a volume is divided into planes, parallel planes become a grid, and the grid is rotated, and so on (figure.34). In the Guardiola house, for example, the design seems to be the result of letting an L-shape roll down the hill where the project is located (figures.35, 36). In later projects, this dynamic notion of transformation is also pursued. At the same time, “the origin of the forms is sought in themes that are related to the location or character of the project” [4].

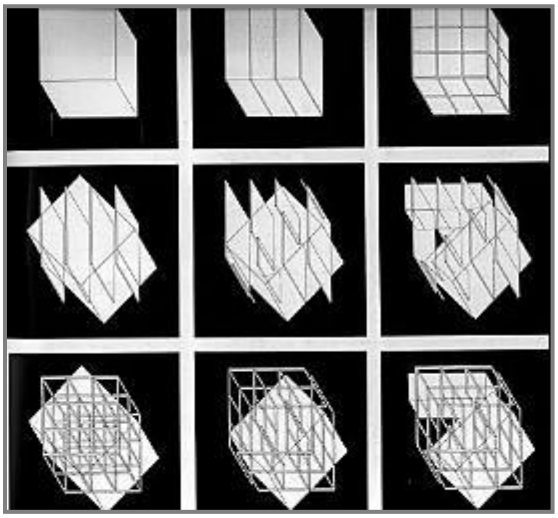


Figure 34: P. Eisenman, Diagrams of House III.

(Source: http://caad.arch.ethz.ch/teaching/nds/ws98/script/object/st-object3.html)

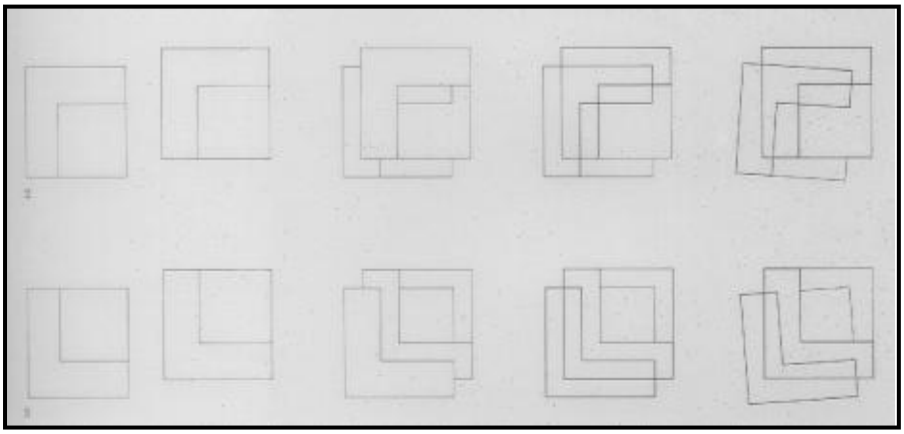


Figure 35: Plan transformation, P. Eisenman. Guardiola House, Cadiz, 1988(Jörg Rügemer, 2000)

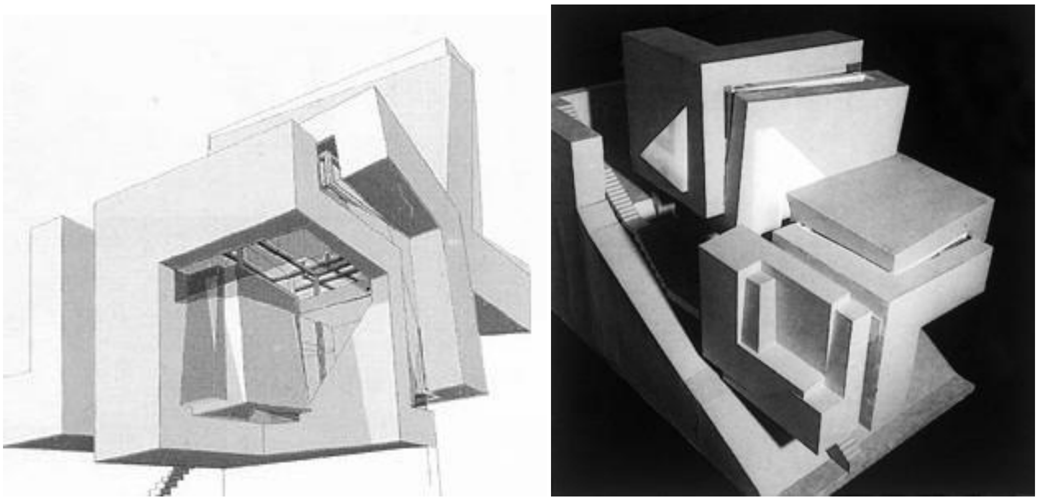


Figure 36: Isometric and model, P. Eisenman. Guardiola House, Cadiz, 1988.

(Source 1: http://caad.arch.ethz.ch/teaching/nds/ws98/script/object/folding.html & http://www.anghelos.org)

4.1.2. Theory of Hypersurface:

Over the last decade or so, the electronic era is transforming these two polarities: "image and form", each within its own context. Stephen Perrella is an architect and editor/designer at the Columbia University Graduate School of Architecture Planning and Preservation with Bernard Tschumi. Stephen Perrella began exploring the relationship between architecture and information in 1991 on Silicon Graphics workstations. In the context of that speculation he focused on "the dynamics of incommensurate relations between form and image" as a formative method for a critique of representation that he has developed into a discourse called "hypersurface”. Among the facets of this theoretical construct include topologies that emerge from interstitial, ambiguous relations between sign Since that time, topological strategies in architecture have become a dominant trend stemming from both a rising, general interest in the discourse of Gilles Deleuze and Felix Guattari, but also through new forms made possible by “animation and particle based computer software” [5]. Hypersurface architecture is Perrella’s concept “for informational and spatial structures that respond critically to the cultural transformations” (Zellner, P, 1999).

Perrella’s earliest hypersurface study, “the institute for electronic clothing experimented with texture-mapping and coordinate-manipulation using three dimensional modeling software”. First, a computer generated wire frame model was deconstructed. The model’s coordinates were then stretched, pulled, tweaked, bent, enfolded and warped, resulting in a form that might be better described as a fabric than an object, over which or through which texture mapping can be used. A seminal construct emerges: “a radical relationship between form and image that rejects, rather than polarizes, the usual dichotomies of structure ornament or substance signification. Form is neither augmented nor enriched by image; rather, image and form are seamlessly integrated, flowing into each other as a unified topology” (Zellner, P, 1999). This was the main outline of the Hypersurface theory. Thus; the thesis has taken two concepts of Stephen Perrela’s theory which illuminate the main points of his thought. The two concepts are:

4.1.2.1. Mobius House: Hypernurban Architecture:

Designed in collaboration with Rebecca Carpenter, this theoretical project (1997-98) explores the hypersurface to consider how we dwell in relationship to communications media. A study diagram for post-Cartesian dwelling, Mobius house is neither an interior space nor an exterior form, but a transversal membrane that reconceptualizes the conventional relationship between interior and exterior into a continuously deformed bridging surface. Peter Zellner (1999) in his book “New Forms in Digital Architecture” stated that the structure’s hypersurface of Perrella’s Mobius House “was derived by initially atomizing the supporting geometry of a

NURB so that each of the five control points governing the NURB could be animated along the path of a Mobius surface” (figure 37) (Zellner, P, 1999).

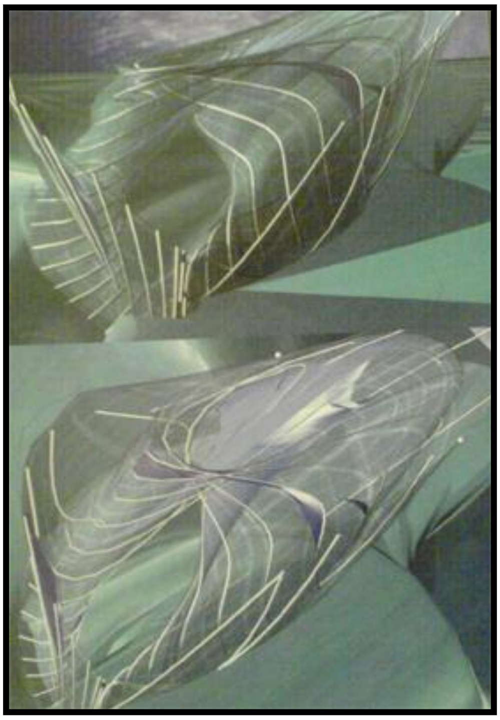


Figure 37: The rotational studies from the animated sequence showing the transformations of the interior and exterior surface. (Zellner, P, 1999).

4.1.2.2. Hypersurface Panel Studies:

Perrella developed this series of variant panel studies (1997-98) to present a viable physical model of a hypersurface. As structural diagrams the panels seamlessly enfold flexing lines of ribbed, interlocked steel or aluminum frames with a mesh like metal fabric or synthetic membrane. The standard division between structure and skin usually “upheld” in architecture is totally enmeshed in these studies. “Layers of fabric seems to implode, engendering fluid interpermulations with the complicated frames; panels demonstrate continuous and consistent inflection between structure and surface in which both intertwined systems interfold in unison to create transversal interrelations from specific distortions” (figures 38, 39) (Zellner, P, 1999).

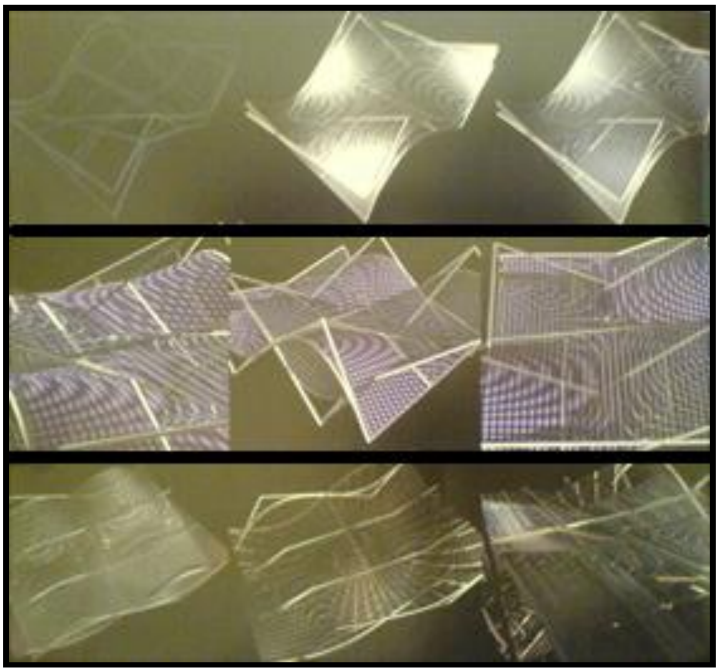


Figure 38: The structural diagram of the panel studies, (Zellner, P, 1999).

Figure 39: The fluidity of the implode layers with the complicated frames and panels, (Zellner, P, 1999).

Briefly; the hypersurface theory investigates the relationship between image and form in which they integrate into each other to create the topological shape.

4.2. Digital Design Methods

The study will introduce the common methods used in digital design during the design process. The ongoing tools of digital design as mentioned before such as rhinoceros, 3ds max, Maya, etc. with their abilities of modeling and visualization depending on some new methods that have entered the field of architecture in the last decade. Those methods such as NURBS, surfaces mesh, and others which will be clarified in this section. By the emergence of those methods in architectural design has shifted the way of thinking in architecture by facilitating the process of creating any type of form that was impossible to achieve. Thus; the thesis introduces the most common used methods of digital design that recently have been discovered to create the form in architecture.

Particularly; by the aid of using digital methods in the design process, the object now can be converted geometrically to a variety of geometrical types that can be reshaping freely by one of the following methods; “an editable mesh, editable poly, editable patch, or NURB Sobject”. Also the 2D shapes like Spline shapes can be converted to an “editable mesh, editable spline, or NURBS object”. Those methods make the ability of creating any complicated form possible to achieve. The following table includes common types of digital design methods which will be defined individually through this chapter. The definitions have been elicited as argued among different professional soft-wares such as 3D Studio max, MAYA, Rhinoceros, and others.

Digital Design Methods
• Mesh / Editable Mesh
• Editable Poly
• Editable Patch Object / Vertex / Edge / Element
• NURBS
• Morphing
• Lofting
• Subdivision surface

Table 4: Digital design methods, (Autodesk® 3ds Max® 9/8 index).

4.2.1. Mesh and Editable Mesh

Mesh as mentioned among some different software such as 3Ds max, Rhinoceros, form-Z, lightwave, Maya, and nPower-nurbs is said to be a method that convert, refines or reshapes every regular shapes into irregular shapes. The original shape is divided into pieces (patches / polygon / vertex / faces). Each piece is converted, refined and/or reshaped by moving, rotating or extended, etc. A new Free-form is created by using meshes.

Whereas; “An editable mesh is a type of deformable object; it uses triangular polygons”. Editable meshes are useful for creating simple, low-polygonal objects or control meshes. A NURBS or patch surface can be converted to an editable mesh; and are “a natural method of modeling with polygonal objects” (Autodesk® 3ds Max® 9/8 index).

The capability of Meshes can be summarized as following:

- Converting any 2D or 3D shapes or surfaces to subdivided once, that has multi-subdivision parts called “vertex or patches” which can be easily controlled or changing into any required form by moving, extruding, deleting or shifting the vertex or the patches to wherever.
- It offers the ability to bend, twist, extend, Boolean or holing any type of primitive forms to be converted into new free form.
- Defining the structure of any irregular shapes (Wire frame).

Another significant factor that should be identified is the effect of Surfaces Mesh on primitive objects (regular objects). Basically; Primitive objects can be controlled and created by using mesh method. Geometrically, as many other ways of defining 3D shapes the objects can be controlled by surfaces mesh which control the five main elements of an object namely “vertex, Edge, Face, Polygon and Element” (Autodesk® 3ds Max® 9/8 index). Those elements have the ability to be controlled for converting any primitive objects to become free form which can be reshaped or improved again into another one.

The following illustration shows the main five elements of geometrical object and how the mesh method converting the primitive objects into free forms or any desired form.

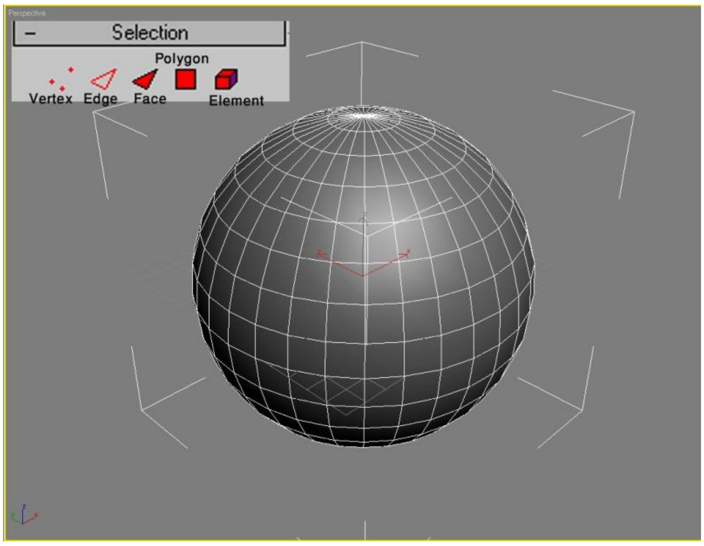


Figure 40: The five elements of geometrical object.

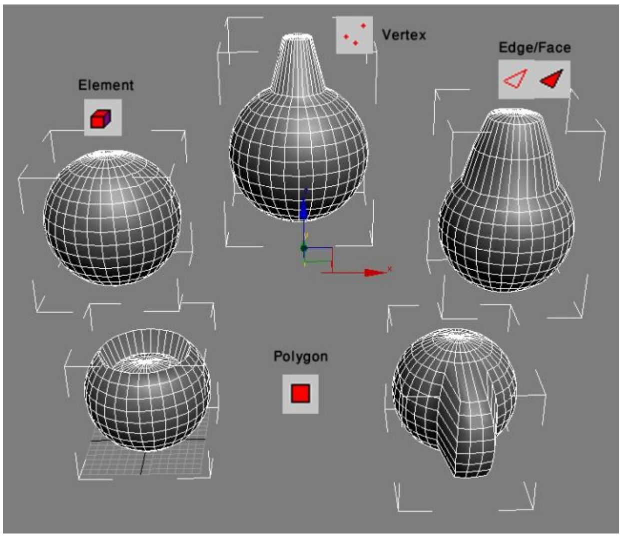


Figure 41: Editable mesh method on primitive shapes

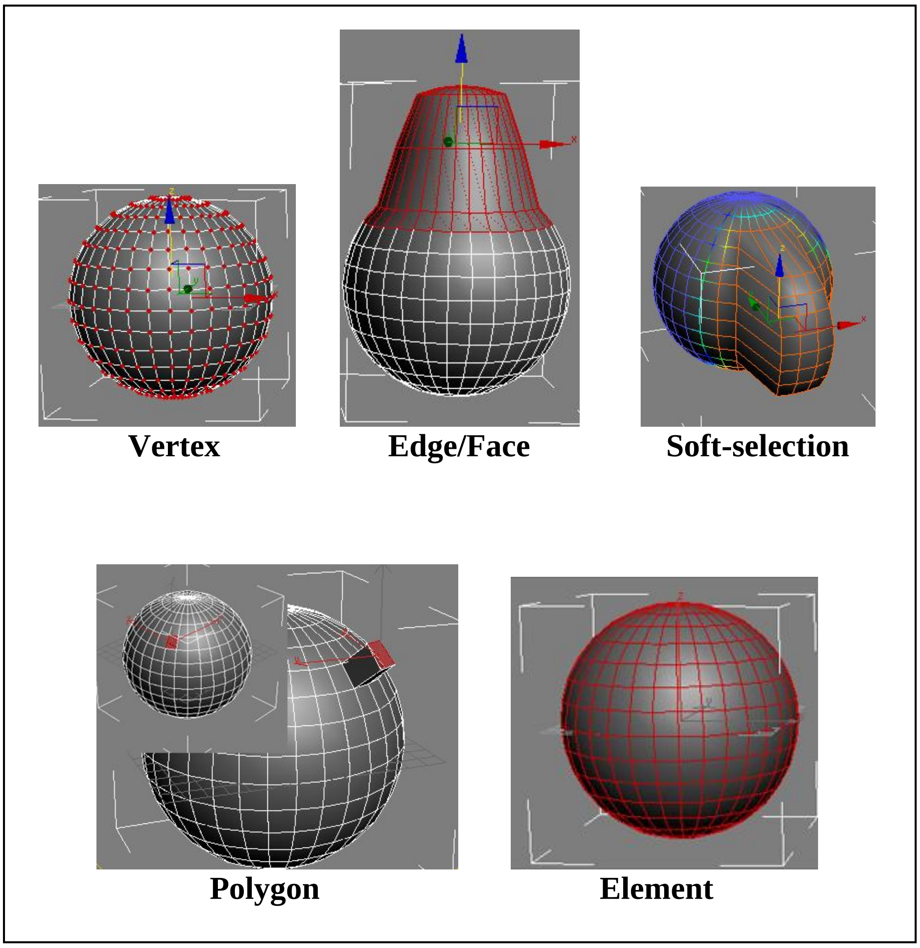


Figure 42: The main five tools of Editable-mesh/poly on primitive objects

4.2.2. Editable Poly

Editable poly is similar to Editable Mesh, but lets to work with polygons of four or more sides, and provides a greater range of functionality. "NURBS surfaces, editable meshes, splines, primitives, and patch surfaces can be converted to editable poly" (Autodesk® 3ds Max® 9/8 index).

4.2.3. Editable Patch

Editable Patch provides controls for manipulating an object as a patch object and at five sub-object levels: "vertex, handle, edge, patch, and element" (Autodesk® 3ds Max® 9/8 index). As used in some different software, unlike others; at 3ds max the editable patch method has the following techniques:

- An example of editable patch object shows a tube object before patching and after patching (figure 43).

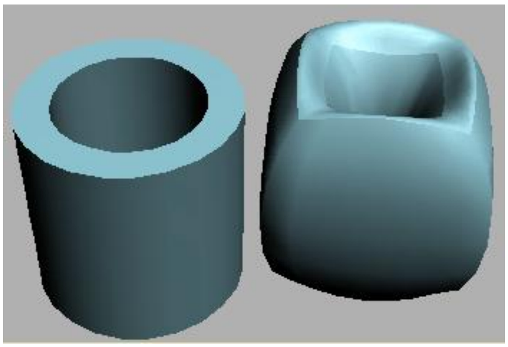


Figure 43: An example of editable patch object, (Autodesk® 3ds Max® 9/8 index)

- An example of editable patch vertex showing that the vertexes of any object or surface can be removed, rotated, arrayed, mirrored, and connected to another to complete the desired shape (figure 44).

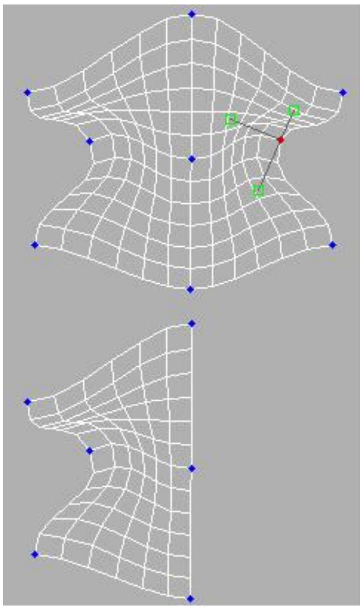


Figure 44: An example of editable patch vertex, (Autodesk® 3ds Max® 9/8 index)

- An example of editable patch edge showing the object's edges selected and can be controlled geometrically (figure 45).

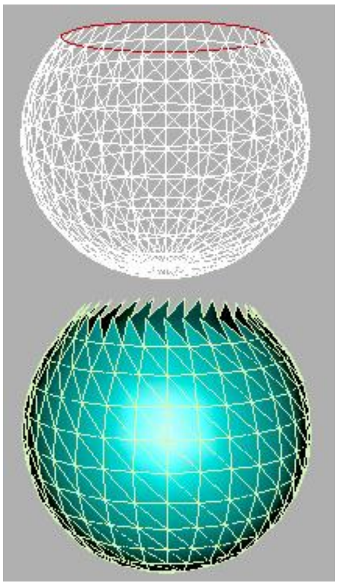


Figure 45: An example of editable patch, (Autodesk® 3ds Max® 9/8 index)

- an example of editable patch element that has the ability to control the only the border of an object or surface (figure 46).

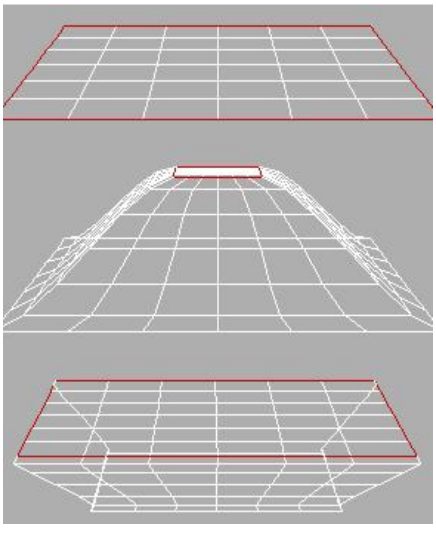


Figure 46: An example of editable patch element, (Autodesk® 3ds Max® 9/8 index)

4.2.4. NURBS

4.2.4.1. Definition of NURBS:

"NURBS, Non-uniform rational B-Splines are mathematical representations that can precisely model any shape from a simple two-dimensional line, circle, arc or box to the most complex three-dimensional free-forms, organic surfaces or solids. Flexibility and accuracy allow NURB models to be used in any computational process from illustration, CAD and animation, to CAM" (Zellner.P, 1999).

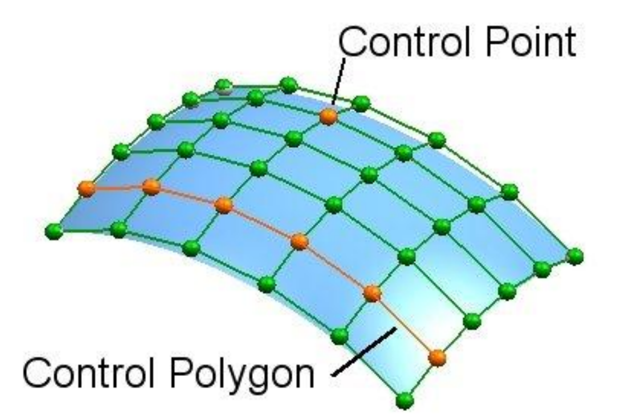


Figure 47: Elements control of NURBS surfaces.

(Source: http://en.wikipedia.org/wiki/image:surface1.jpg)

NURBS is an acronym for Non-Uniform Rational B-Splines:

Non-Uniform refers to "the parameterization of the curve. Non-Uniform curves allow, among other things, the presence of multi-knots, which are needed to represent Bezier curves".

Rational refers to "the underlying mathematical representation. This property allows NURBS to represent exact conics (such as parabolic curves, circles, and ellipses) in addition to free-form curves".

B-splines are "piecewise polynomial curves that have a parametric representation" (Maya index, 2003)

4.2.4.2. History of NURBS

Development of NURBS began in “the 1950s by engineers who were in need of a mathematically exact representation of freeform surfaces” like those used for car bodies and ship hulls, which could be exactly reproduced whenever technically. Needed, Prior representations of this kind of surfaces only existed as a single physical model created by the designer.

The pioneers of this development were “Pierre Bezier who worked as an engineer at Renault, and Paul de Casteljau who worked at Citroën, both in France”. Bezier worked nearly parallel to de Casteljau, one not knowing about the work of the other. But because Bezier published the results of his work, the average computer graphics user today recognizes splines — which are represented with control points lying on the curve itself — as “Bezier splines”, while de Casteljau’s name is only known and used for the algorithms he developed to evaluate parametric surfaces. “In the 1960s it became clear that non-uniform, rational B-splines are a generalization of Bezier splines, which can be regarded as uniform, non-rational B-splines” (Maya index, 2003).

At first NURBS were only used in the proprietary CAD packages of car companies. Later they became part of standard computer graphics packages, including the OpenGL Graphics Library.

Real-time, interactive rendering of NURBS curves and surfaces were first made available on “Silicon Graphics workstations in 1989”. In 1993, the first interactive NURBS modeler for PCs, called “*NöRBS”*, was developed by “CAS Berlin”, a small startup company cooperating with the Technical University Berlin. Today most professional computer graphics applications available for desktop use offer “NURBS technology”, which is most often realized by integrating a NURBS engine from a specialized company. (Les Piegl & Wayne Tiller, 1995-97), (Dr. Lyle Ramshaw, 1987), (David F. Roger, 2001), (Foley, van Dam, Feiner & Hughes, 1996) [6], [7].

4.2.4.3. Use of NURBS

NURBS are nearly “ubiquitous” for computer-aided design (CAD), manufacturing (CAM), and engineering (CAE) and are part of numerous industry wide used standards, such as “IGES, STEP, ACIS, and PHIGS”. However, there is still a lot of confusion about NURBS's advantages and usefulness for interactive modeling, due mostly to guesswork based on knowledge about a single software package and the usability of its user interface. In general, it can be said that editing NURBS curves and surfaces is highly intuitive and predictable. Control points are always connected either directly to the curve/surface or act as if they were connected by a rubber band. “Depending on the type of user interface, editing can be realized via an element’s control points, which are most obvious and common for Bezier curves, or via higher level tools such as spline modeling or hierarchical editing” (Les Piegl & Wayne Tiller, 1995-97), (Dr. Lyle Ramshaw, 1987), (David F. Roger, 2001), (Foley, van Dam, Feiner & Hughes, 1996), [8].

The study briefly finalized the capabilities of NURBS as following:

1. They offer one common mathematical form for both, standard analytical shapes (e.g. conics) and free forms shapes.
2. Provide the flexibility to design a large variety of shapes.
3. Can be evaluated reasonably fast by numerically stable and accurate algorithms.
4. By its richness of line types and other surface elements it can be easily create and control the geometry of the required form.

4.2.4.4. Modeling by NURBS:

NURBS surfaces and curves, have become an industry standard for designing and modeling surfaces. They are especially suited for modeling surfaces with complicated curves. The method of modeling with NURBS does not require an understanding of the mathematics that produces these objects. NURBS are popular because they are easy to manipulate interactively, and because the algorithms that create them are both efficient and numerically stable.

It's also possible to model surfaces using polygonal meshes or patches. Compared to NURBS surfaces, meshes and patches have these shortcomings:

- Using polygons can make it more difficult to create complicated curved surfaces.
- Because meshes are faceted, facets appear at the edge of rendered objects. The object must have a large number of small faces to render a smoothly curved edge.

NURBS surfaces, on the other hand, "are analytically generated. They are more efficient to calculate, and also possibly to render a NURBS surface that appears to be seamless" [9].

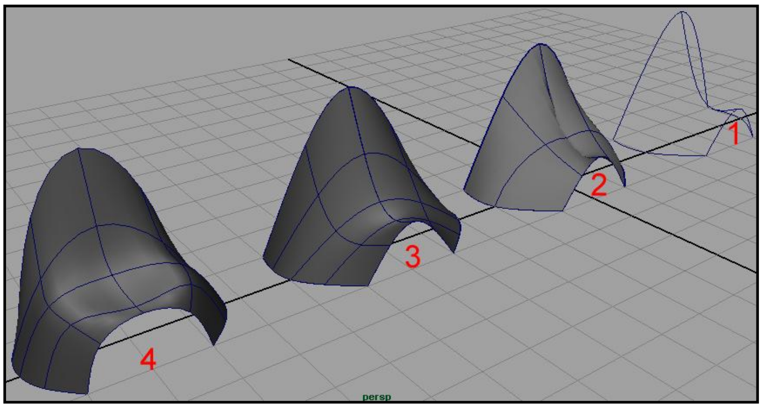


Figure 48: Creating surfaces by using CV curves through NURBS
(Source: http://bigrocket.tripod.com/id21.html)

NURBS Surfaces: NURBS surface objects are the basis of NURBS models. "NURBS surface can be modified by moving CVs or NURBS points, attaching other objects, creating sub-objects, and so on" (Autodesk® 3ds Max® 9/8 index). There are two kinds of NURBS surfaces; Point Surface and CV Surface:

- **Point Surface:**

Point surfaces are NURBS surfaces whose points are constrained to lie on the surface. See (figure 49).

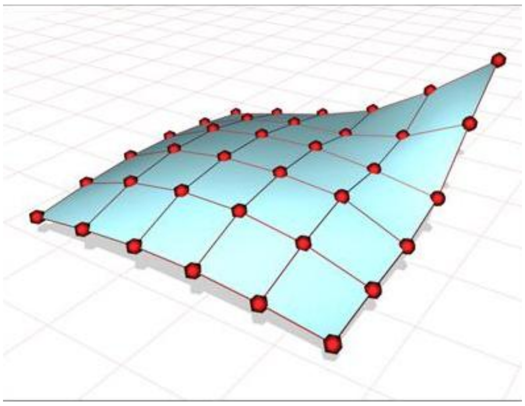


Figure 49: Points shape the surface they lay on, (Autodesk® 3ds Max® 9/8 index)

- **CV Surface:**

CV surfaces are “NURBS surfaces controlled by control vertices (CVs)”. The CVs don't lie on the surface. They define “a control lattice” that encloses the surface. Each CV has a weight that can be adjusted to change the shape of the surface as shown in (figure 50) (Autodesk® 3ds Max® 9/8 index).

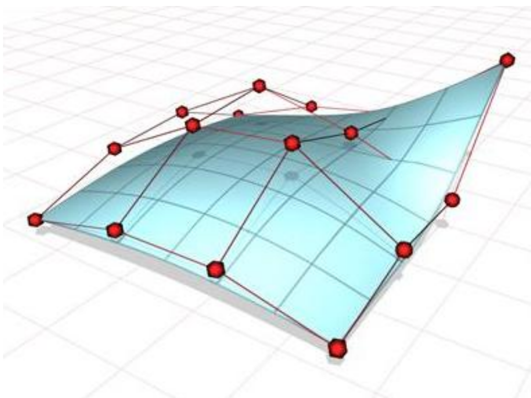


Figure 50: The CVs in a control lattice shape the surface it defines, (Autodesk® 3ds Max® 9/8 index).

It can be also create a NURBS surface from a geometric primitive as shown in (figure 51).

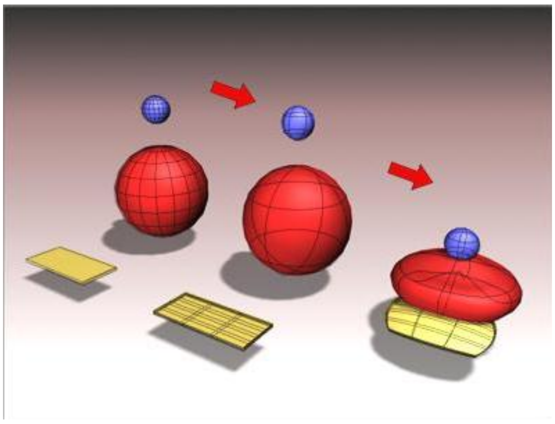


Figure 51: Primitive objects become NURBS surfaces
That can be then edited in various ways, (Autodesk® 3ds Max® 9/8 index).

4.2.4.4.1. Creating Form by using NURBS surfaces

The study has taken the following experiment as a sample using 3ds max to create a predictable form by using the method of NURBS surfaces.

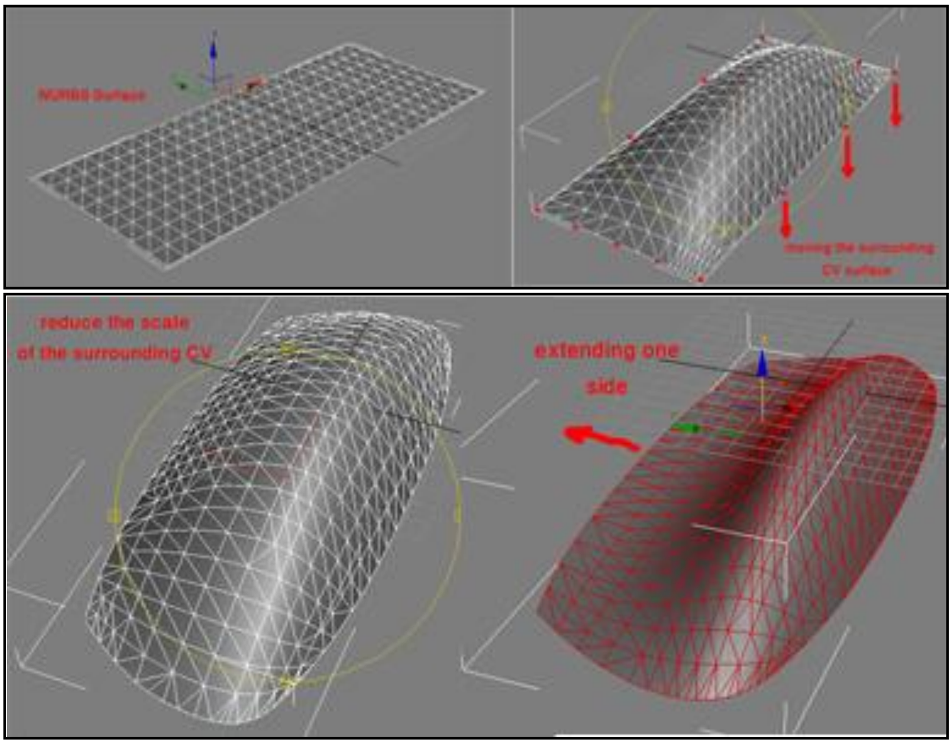


Figure 52: using NURBS surfaces step one

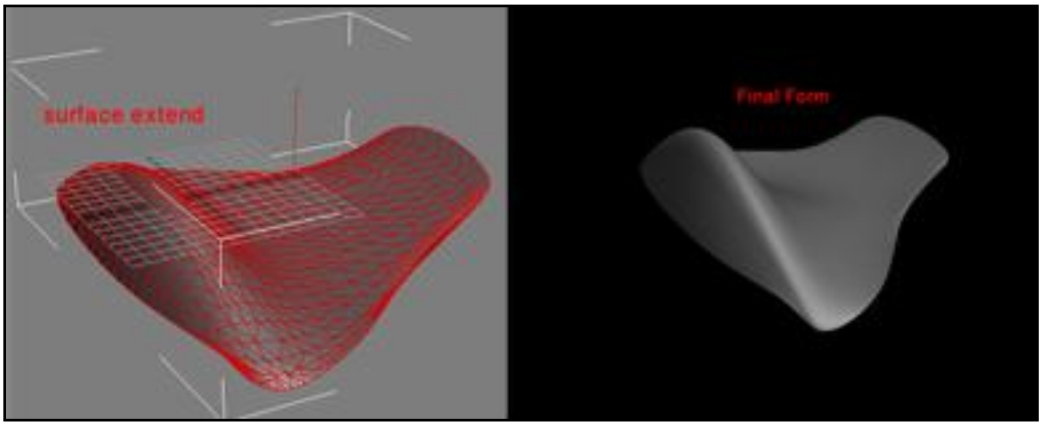


Figure 53: Using NURBS surfaces final result.

4.2.4.4.2. Creating form by using CV curves

1- Building three NURBS curves, two curves should be parallel to each other on the X or Z axis.

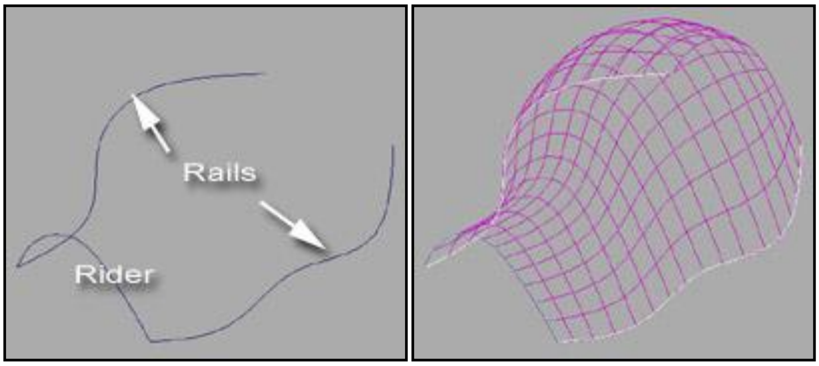


Figure 54: Building three NURBS curves.

(Source: http://bigrocket.tripod.com/id21.html)

2- By using NURBS surfaces modification, A NURBS surface will be created according to how the curves are laid out.

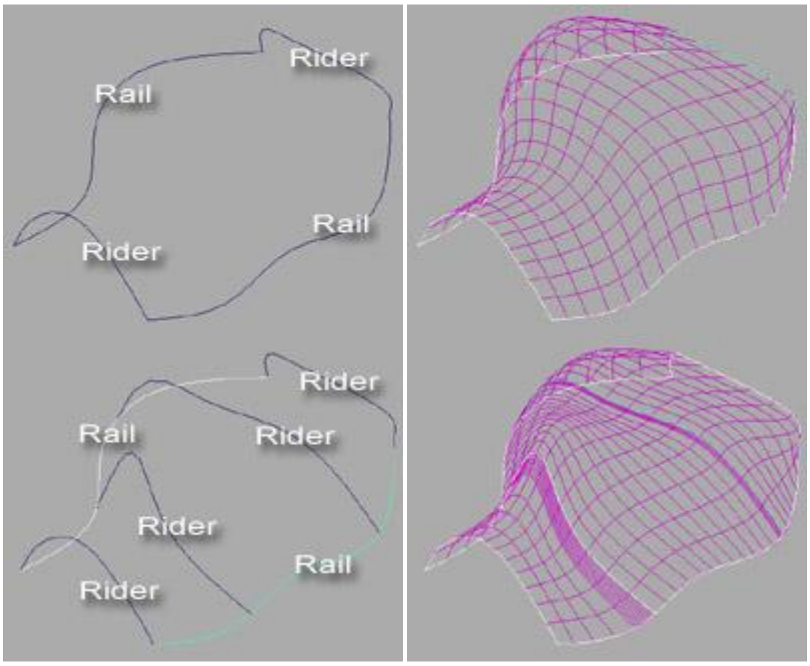


Figure 55: Using NURBS surfaces modification.

(Source: http://bigrocket.tripod.com/id21.html)

By building two or more wire frames connecting the shape sides together, The NURBS surfaces will be created and also the segments values will be inserted.

3- The shape can be controlled by the wire frames or the intersected points (vertex).

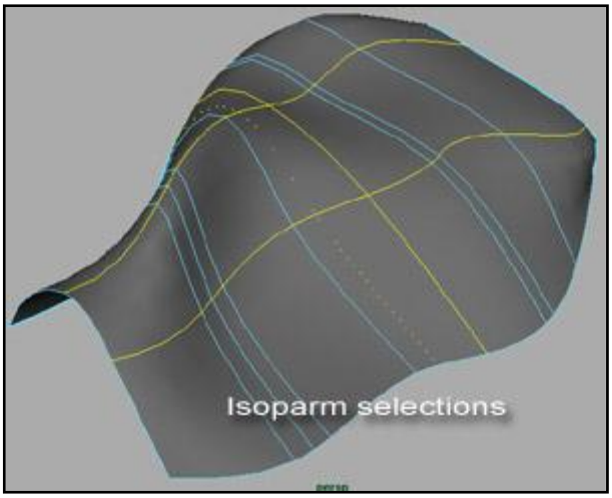


Figure 56: Controlling the shape by wireframes or vertex.

(Source: http://bigrocket.tripod.com/id21.html)

4- Also it can be drown some single curves on the surfaces for holing or cutting some randomly parts on the main surface.

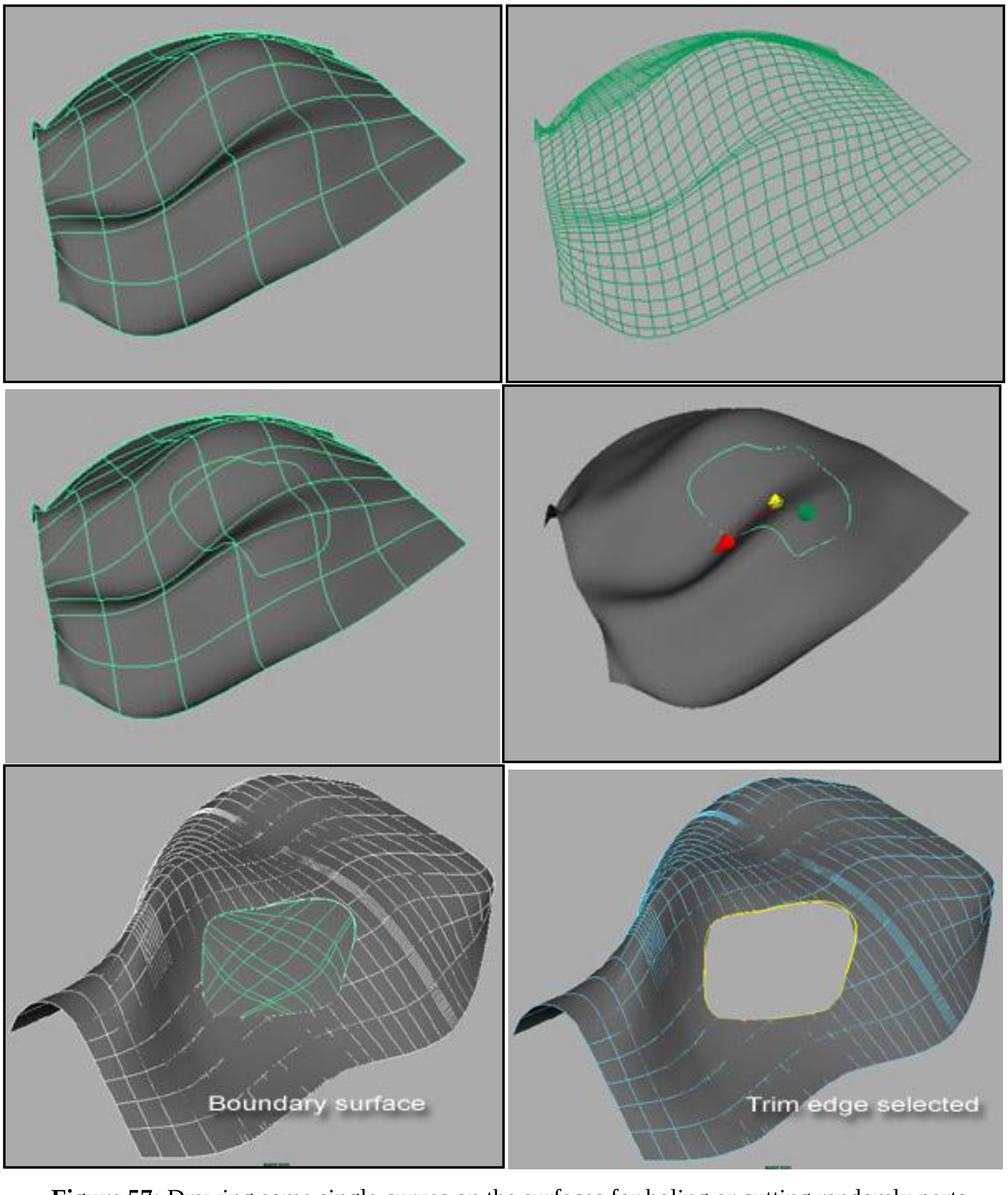


Figure 57: Drawing some single curves on the surfaces for holing or cutting randomly parts.
(Source: http://bigrocket.tripod.com/id21.html)

The best example of using the NURBS method can be seen at Frank Gehry’s Guggenheim museum in Bilbao and some other offices like NOX in there project “Quartie De L’enfant”.

Figure 58: Frank.O.Gehry’s Guggenheim museum in Bilbao.

(Source: http://www.guggenheim-bilbao.es/ingles/edificio/el_edificio.htm)

Figure 59: QUARTIER DE L'ENFANT, BY NOX.

(Source: http://www.europaconcorsi.com)

4.2.5. Morphing

"Morphing is an animation technique similar to tweening in 2D animation". A Morph object combines two or more objects by "interpolating the vertices of the first object to match the vertex positions of another object". When this interpolation occurs over time, a morphing animation results as shown in (figure 60). The original object is known as the "*seed* or *base"* object. The object into which the seed object morphs is known as the "*target*" object (Autodesk® 3ds Max® 9/8 index).

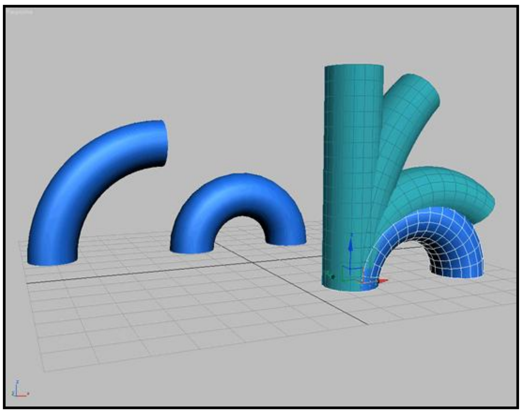


Figure 60: Morphed object using single targets that make the object vibrating, (Autodesk® 3ds Max® 9/8 index)

The new Korean Presbyterian Church of New York by Greg Lynn; is the best example about how this method could be used in building.

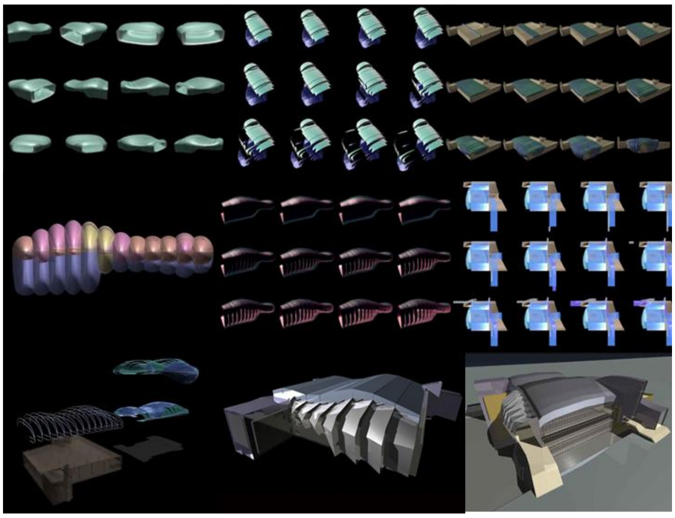


Figure 61: generating the form using morphing method on the Korean Presbyterian Church of New York, Greg Lynn, 1995-99

(Source: http://www.a-matter.de/digital-real/eng/main.asp?pr=6,available)

4.2.6. Lofting:

Lofting is an important method for 3D object creation. It creates shape objects to serve as a path and any number of cross-sectional shapes. "The path becomes the framework that holds the cross-sections forming the lofted object" (Autodesk® 3ds Max® 9/8 index). Once a loft object has been created, it can be changing and animating its parameters and sub-objects.

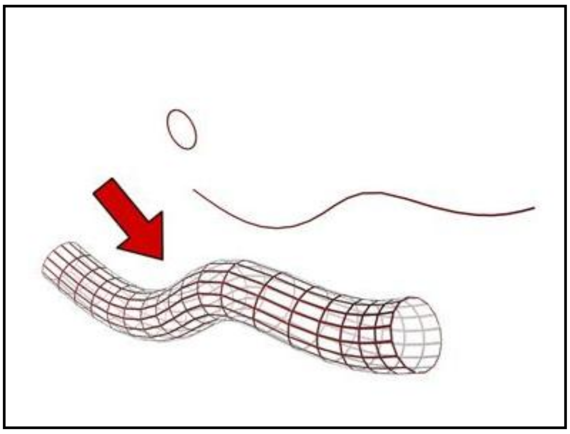


Figure 62: A circle is lofted along a path to construct a tubular shape, (Autodesk® 3ds Max® 9/8 index)

The term lofting comes from early shipbuilding. A large framework called a loft was built to hold the hull of a ship while it was assembled. The process of hoisting the ribs (cross-sections) of the hull into the loft became known as "lofting" (Autodesk® 3ds Max® 9/8 index).

"Loft objects are two-dimensional shapes extruded along a third axis" (Autodesk® 3ds Max® 9/8 index). Creating loft objects from two or more existing spline objects and one of these splines serves the path. The remaining splines serve as cross-sections, or shapes, of the loft object. While the shapes being arranged along the path, the graphical software such as 3ds max, Maya**,** or others has the ability to generate a surface between the shapes.

While creating the shape objects to serve as a path for any number of cross-section shapes, the path becomes the framework that holds the cross sections forming the requested object. If only one shape designated on the path, the computer software like “**3Ds max**” assumes an identical shape that will be located at each end of the path. The surface is then generated between the shapes. See (figures 64, 65, and 66).

Note:

- It can't be **animate** the path location of a shape.
- It can be convert the loft objects to **NURBS** surfaces (Autodesk® 3ds Max® 9/8 index).

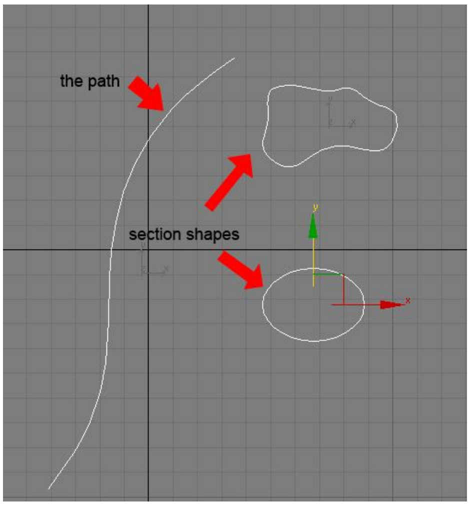


Figure 63: Path and section shapes used for lofting.

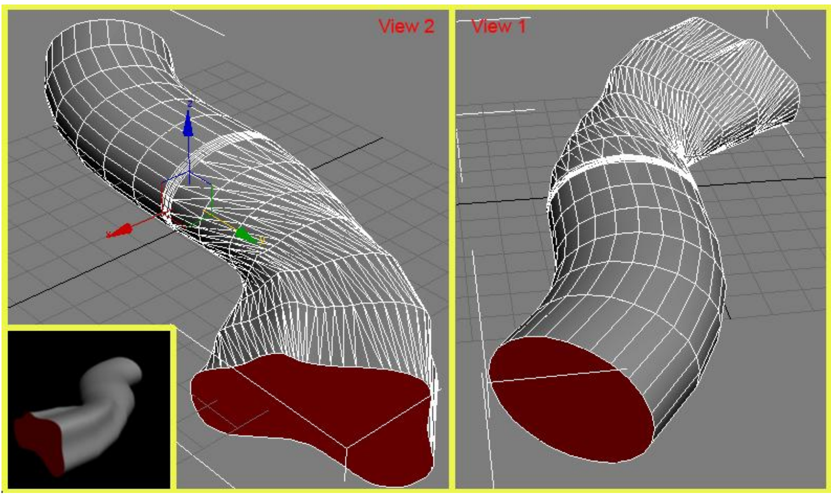


Figure 64: The lofted form by using two different section shapes.

Figure 65: Eisenman, MUSEE DES CONFLUENCES, 2001, LYON-FRANCE

(Source: http://www.eisenmanarchitects.com)

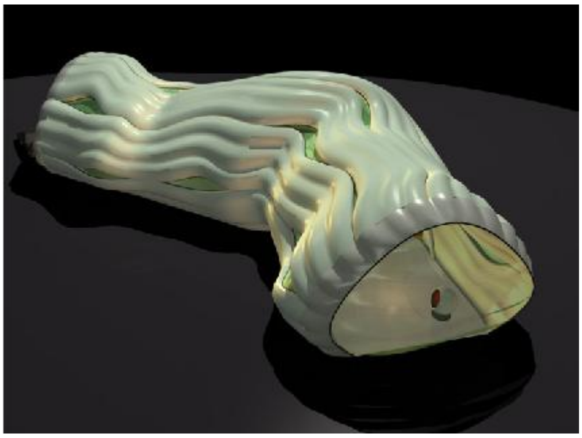


Figure 66: 3rd gear house by NOX, (Lars Spuybroek, 2004)

4.2.7. Subdivision Surface

In computer graphics, subdivision surfaces are used to create smooth surfaces out of arbitrary meshes. “Subdivision surfaces are defined as the limit of an infinite refinement process”. They were introduced simultaneously by Edwin Catmull and Jim Clark, and by Daniel Doo and Malcom Sabin in 1978. Little progress was made until 1995, when Ulrich Reif solved subdivision surfaces behavior near “extraordinary vertices” [10].

Subdivision surfaces are a unique surface type available for modeling in some different software like Maya, 3ds max, Softimage and others that “possess characteristics of both polygon and NURBS surface types” (Autodesk Maya 8 documentation). Like NURBS surfaces, subdivision surfaces are "capable of producing smooth organic forms and can be shaped using relatively few control vertices". Similarly; like polygon surfaces, subdivision surfaces allow to extrude specific areas and create detail in the surfaces when it is required. This is accomplished by having the ability to work at different component levels of detail on the subdivision surface. Modeling with subdivision surfaces is an easy way to create intricate objects. "It combines the best features of NURBS and polygonal modeling" (Autodesk Maya 8 documentation).

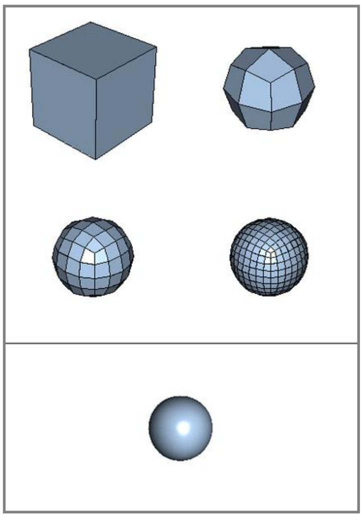


Figure 67: Generating the shape by subdivision steps.

(Source: http://www.ecclectica.ca/issues/2004/2/baumgarnter.asp)

4.2.7.1. Advantages of subdivision surfaces:

- Subdivision surfaces allow higher level control over shape than polygons.
- They allow to only using complex geometry in the complex regions of the required model.
- They allow creases (sharp edges) and arbitrary topology (not just four-sided sheets).
- The continuity of subdivision surfaces eliminates many of the problems that can occur at seams when animating NURBS surfaces.

- Subdivision surfaces can be bind to skeletons at a coarse level and the effects will translate smoothly to the finer levels (Autodesk Maya 8 documentation).

4.2.7.2. Where Subdivision Surfaces Are Used?

İn 3D Modeling and Rendering: Subdivision surfaces are being included in modeling and rendering packages because of their ease of use, and the freedom they allow the designer. They are even beginning to become one of the modeling primitives, which would see them being included in almost every modeling package available.

"Skeletal animation incorporates itself nicely into subdivision surfaces, since the mesh is just dependent on the bones of the underlying skeleton". Once a basic mockup of "a character mesh" is created, and the animation details are worked out, all that the designer should have to do is "subdivide" their mesh. From there, everything will be in complete control of the "skeletal animation system" [11].

3D Scanning: When an object is scanned into a computer using a 3D scanner, there are often artifacts (i.e. small bulges or bumps where there were not any on the original object) or missing areas that the scanner just could not pick up. "Subdivision surfaces could easily take the existing data brought in from the scanner, and interpolate where missing data should be placed, and remove any artifacts from the surface of the mesh" [12]. There are several refinement schemes of subdivision method such Catmull-Clark, Doo-Sabin and Loop

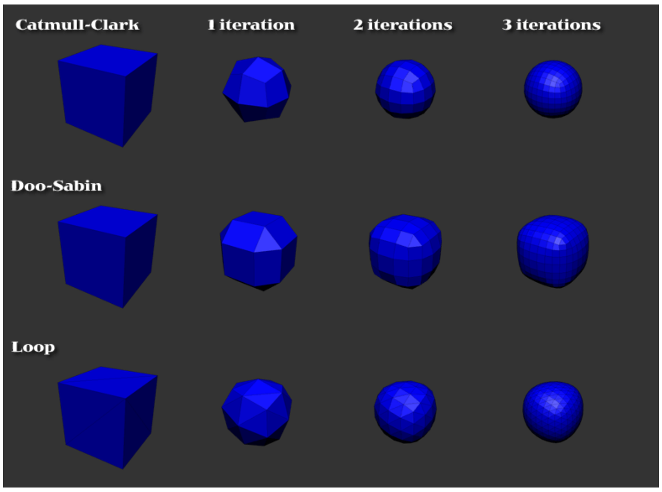


Figure 68: Several refinement schemes of subdivision method.
(Source: http://www.ecclectica.ca/issues/2004/2/baumgarnter.asp)

All the previous techniques can be done to all the primitive objects such as plane, cube, cone, cylinder, sphere, and tube.

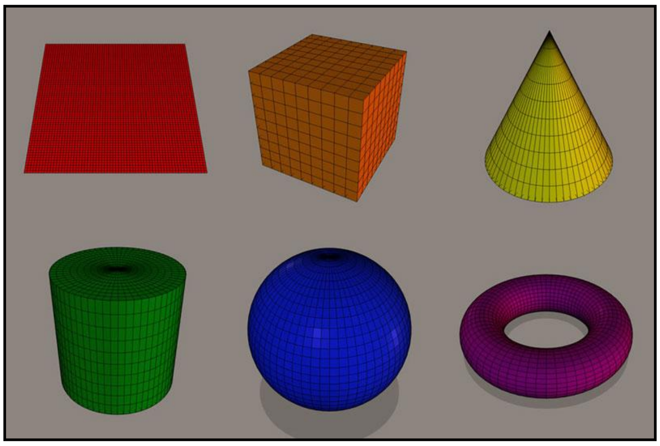


Figure 69: Some primitive objects that can be converted to subdivision surfaces

(Source: http://www.ecclectica.ca/issues/2004/2/baumgarnter.asp)

4.2.7.3. Creating Form by Subdivision Surfaces Method

The following example showing a brief explanation about how to use the method of subdivision surface to create a complicated form using Maya software.

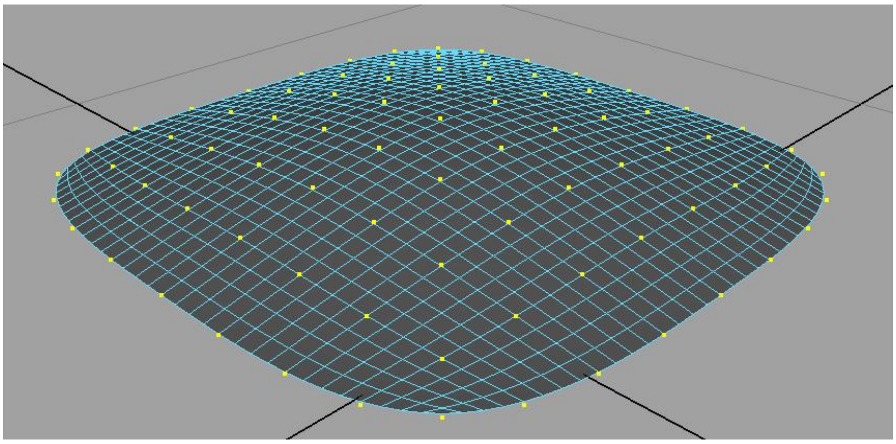


Figure 70: Using standard subdivision surface.

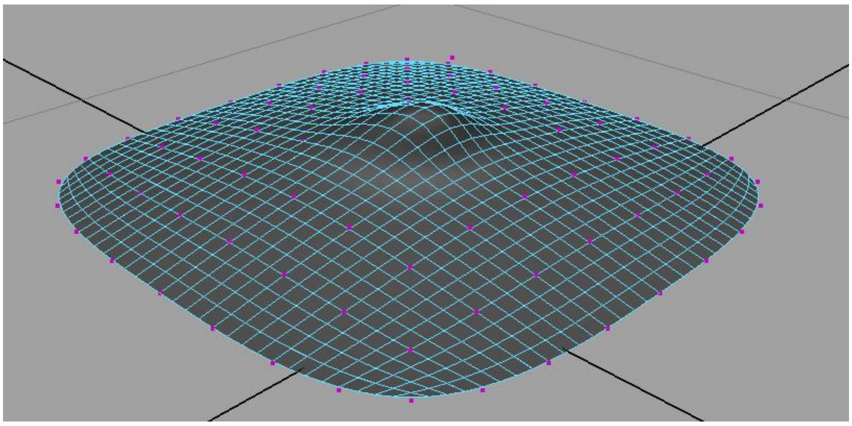


Figure 71: Selecting randomly vertex.

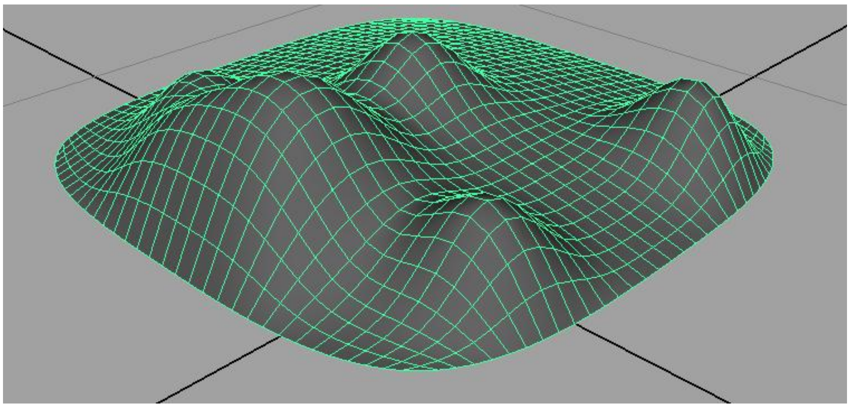


Figure 72: Controlling more than one vertex.

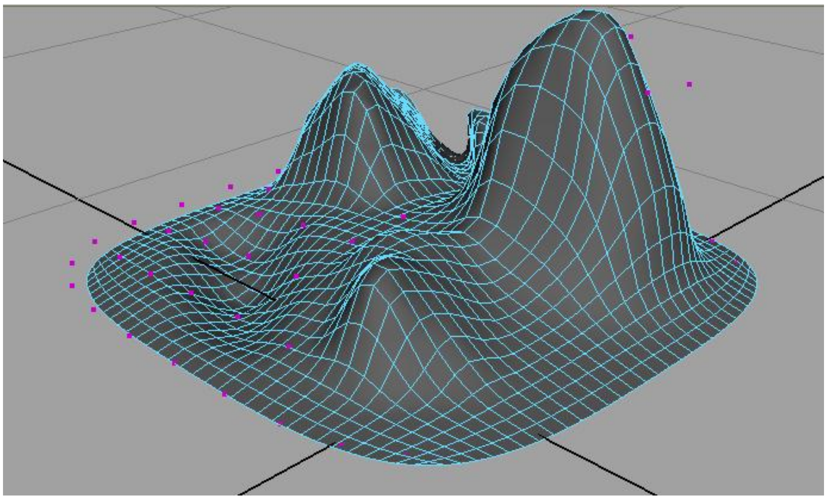


Figure 73: Approximative form.

The best example of using this type of method can be seen on NOX concept of ECB European Central Bank, Frankfurt, Germany, 2003.

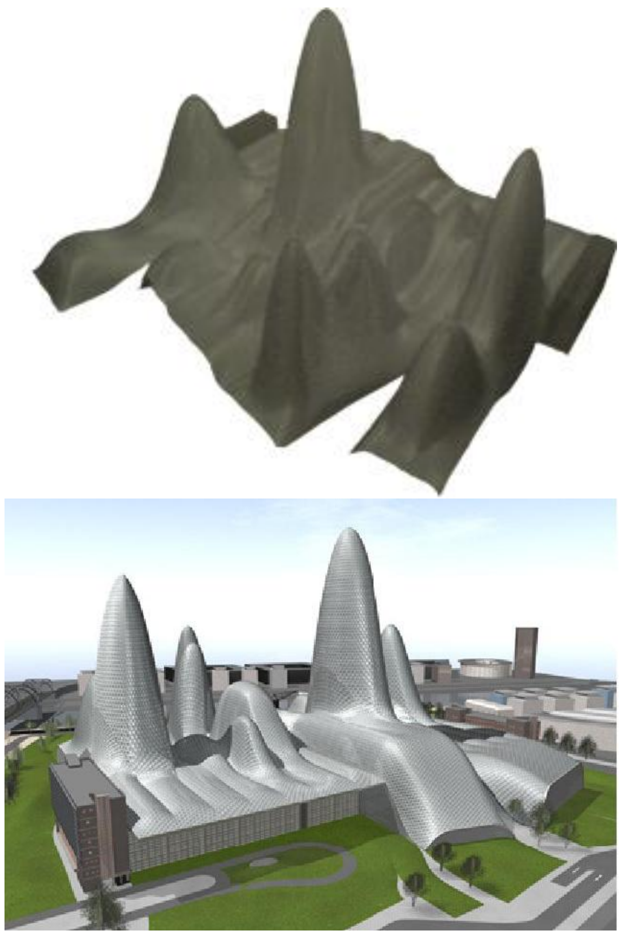


Figure 74: Conceptual and digital model of ECB by NOX, Frankfurt, 2003**,** (Lars Spuybroek, 2004)

4.3. Contemporary Approaches to Digital Form

İn contemporary architecture some new concepts have been emerged which are widely in use specially in the territory of digital architecture. As those concepts are playing more important role in the design process and production of digital form, different approaches have been addressed in following paragraph by giving an example of different architects' work.

4.3.1. Folding:

A design strategy that departs from Euclidean geometry of discrete volumes represented in Cartesian space, and employs topological conception of form and the "rubber-sheet" geometry of continuous curves and surfaces as its ultimate expression. It is one of the many terms and concepts, such as affiliation, smooth and striated space, pliancy, and multiplicity, appropriated from Deleuze's work "The Fold". The Fold or "*le pli*", as defined by Deleuze, posits a post-structuralist notion of space "made up of platforms, fissures, folds, infills, surfaces and depths that completely dislocate our experience" (Rena Logara, 2004).

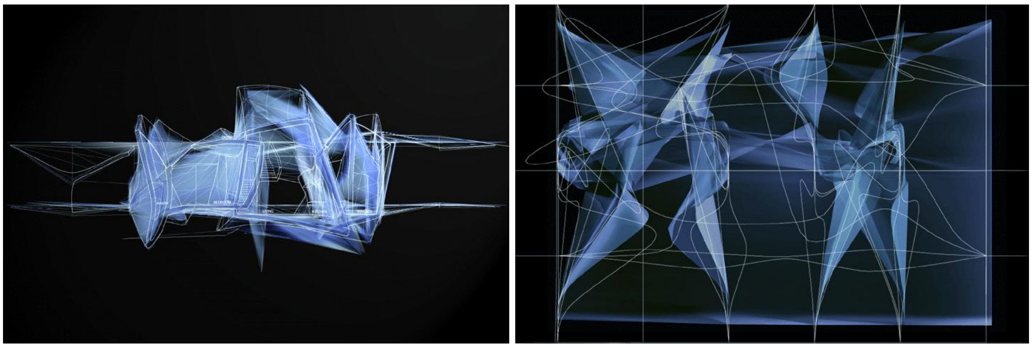


Figure 75: Competition for a Virtual House. 1997, Peter Eisenman.

(Source : http://prelectur.stanford.edu/lecturers/eisenman/)

Figure 76: Some furniture concepts by Zaha Hadid

(Source: http://kosmograd.typepad.com/kosmograd/2006/12/zaha_hadid_is_s.html)

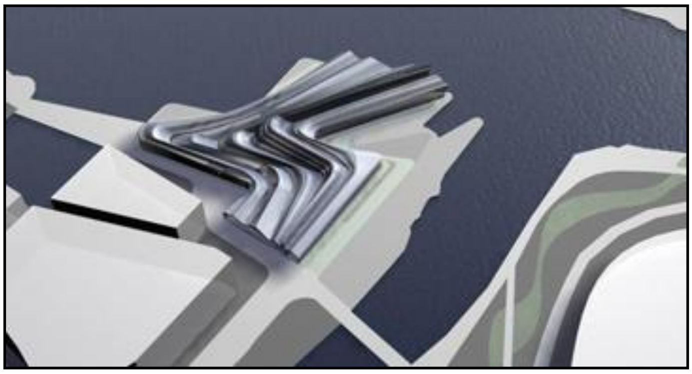


Figure 77: Clyde museum by Zaha Hadid.

(Source: http://www.scottisharchitecture.com/sa/public/article/view/Zaha+Hadid)

4.3.2. Topology (mathematical definition):

"A study of intrinsic, qualitative properties of geometric forms that are not normally affected by changes in size or shape, i.e. which remain invariant through continuous one-to-one transformations or elastic deformations, such as stretching or twisting torus, Mobius strip, Klein bottle". (Rena Logara, 2004)

This quality of homeomorphism is particularly interesting, as focus is on the relational structure of an object and not on its geometry- the same topological structure could be geometrically manifested in an infinite number of forms.

"In the realm of form, the stable is replaced by the variable, singularity by multiplicity". (Rena Logara, 2004)

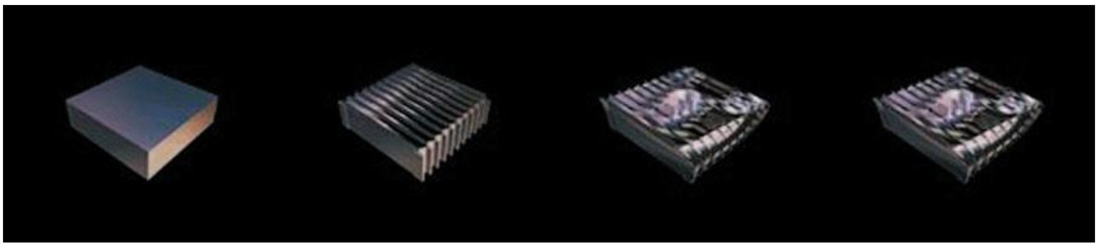


Figure 78: The same topological structure geometrically manifested in an infinite of forms, (Rena Logara, 2004)

4.3.3. Digital morphogenesis:

Instead of modeling an external form, designers articulate an internal generative logic, which then produces, in an automatic fashion, a range of possibilities from which the designer could choose an appropriate formal proposition for further development.

"Digital Morphogenesis," was designed to: "examine methods in contemporary architectural design in which digital media is employed not as a representational tool for visualization, but as a generative tool for the derivation of form and its transformation. The digital morphogenesis explores the possibilities for the 'finding of form,' which the emergence of various digitally based generative techniques seem to bring about" (University of Pennsylvania, 2002), (Rena Logara, 2004).

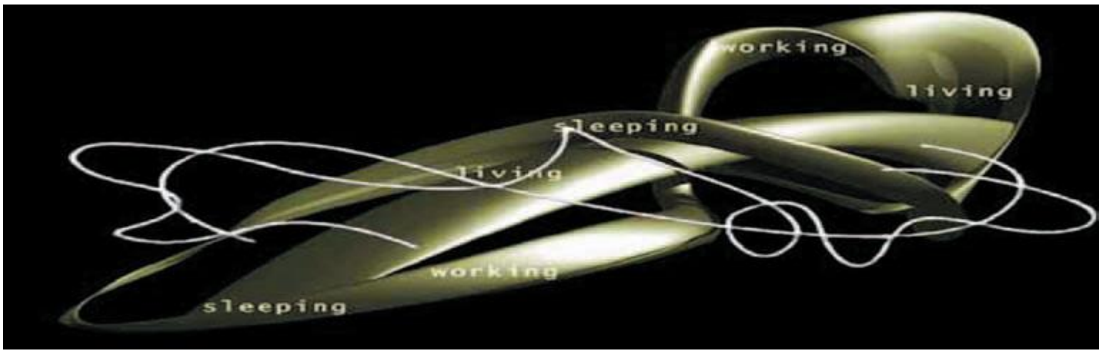


Figure 79: "mobius house", UN studio, (Rena Logara, 2004)

4.3.4. Morphing:

Computerized creation of an animation or transformation in which an image or abject gradually turns into another at certain time. Or as discussed in (Rena Logara, 2004); "smoothly interpolating two different states of formal aggregation into one continuous shape. Its importance is the capability of mutation and trans-placement of certain characteristics of one configuration into other unlimited instances. It involves a transformation between objects of completely different shapes, sizes and forms".

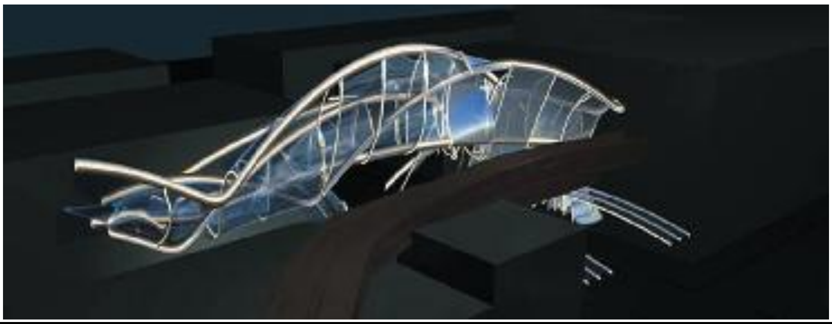


Figure 80: Triple Bridge Gateway, Greg Lynn 1995
(Source: http://www.basilisk.com/P/portauthority_561.html)

The project illustrates Lynn's concept of "simulating the flow of pedestrians, cars and buses" across the site each with different speed and intensities of movement. "The forces of movement were used to establish a gradient field of attraction across the site". To find a form of attraction, Lynn introduced geometrical particles that changed position and shape according to the influence of these forces. The particle studies were used to capture "a series of phase portraits" that showed cycles of movement over a given time period. The phase portraits were then swept with a secondary structure of tubular frames that linked the ramps, surrounding buildings and the terminal. "Eleven tensile surfaces were stretched across the tubes as an enclosure and projection surface" (Zellner, P, 1999).

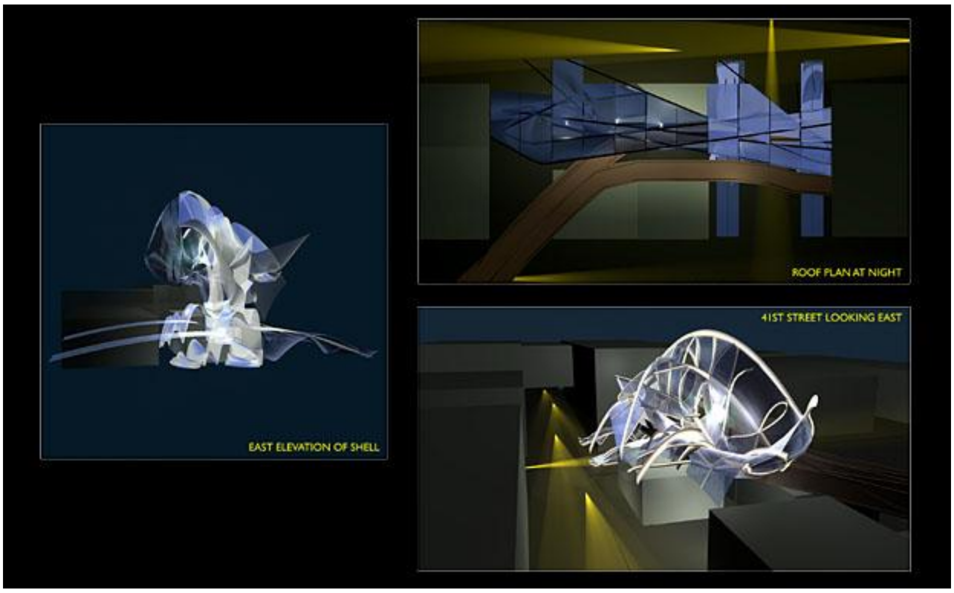


Figure 81: Top right: roof plan, bottom right: street view, left: East elevation, Greg Lynn 1995.
(Source: http://www.basilisk.com/P/portauthority_561.html)

4.3.5. Non-linear systems:

"Systems capable of self-organization, and thus that can spontaneously create order, through often more than one equilibrium state, bifurcation points and transitions from one stable trajectory to another" (Rena Logara, 2004). They are autonomous and certain generic properties may appear despite differentiated systems and contexts.

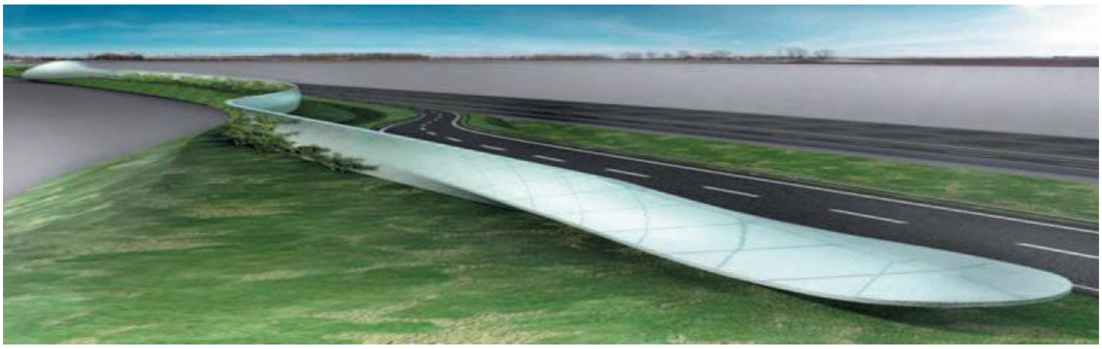


Figure 82: "acoustic barrier", oosterhuis Assosiate

(Source: http://www.oosterhuis.nl/quickstart/index.php?id=302)

CHAPTER FIVE

MODELLING IN DIGITAL FORM

In the early stages of their engagement of computer technology, architects approached the technology as an assistive technology that would enhance the practice of architecture. The key in the development of digital tools to enhance the practice of architecture has been the facility with which the various tasks involved in the practice of architecture have been represented, enabled or enhanced using computer technology. The digital representation of architectural entities and the digital manipulation of those entities have provided alternate means to produce architecture. Drawing, modeling, performance simulation, design collaboration, construction management and building fabrication are now routinely performed using computer based technology. The study classifies the digital tools into two categories: Firstly; the software or conceptual tools (design tools) which assimilated in three dimensional software. Secondly; Hardware or applicative tools (Fabrication tools) which based on digital fabrication machines.

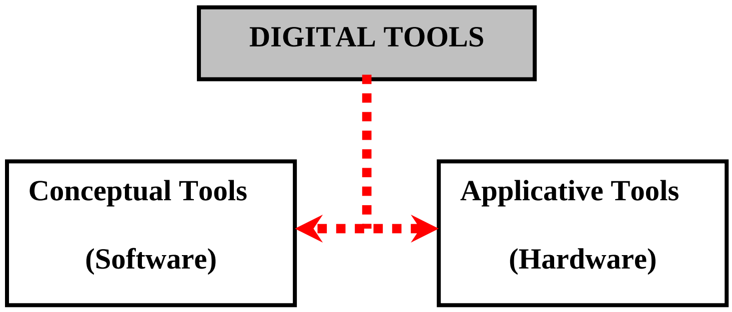


Figure 83: Classification of digital tools.

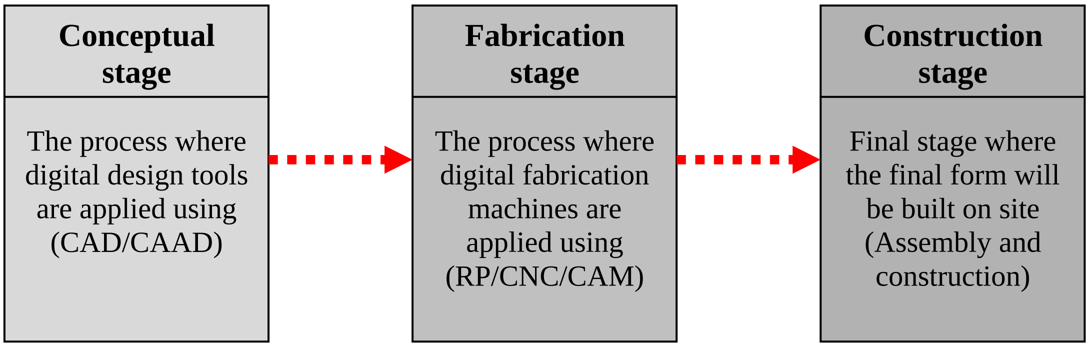


Figure 84: The three main stages of digital design process.

5.1. SOFTWARE: Digital Design Tools

The tools of architectural design in the digital era is considered to be related to the computer softwares which used among all the designer and architects to create any type of forms whether that types was regular or irregular forms.

There are so many softwares that have been discovered to help the designers and architects even the theorists to create and improve thier thoughts or design methods. Some of the most known softwares which have been using in the field of architecture, graphics, and even the Cinema are RhinoCeros, Form-Z, 3D studio Max, Maya, lightwave, and others (Figure 85). Those softwares have proved their capabilities of creating any type of form that had been diffecult to be done by the traditional tools. The study classifies those tools as being used among many architects and designers in thier design process. İt can be seen that they are a little different in their way of modelling shapes even in the way of sketching or producing the free forms.

Basically, they may sharing the same techniques or methods to create the form as a design technique such as using Nurbs technique or surface mesh but the tools and modifications which they contian are a little bit different. Each of those tools “graphic software” are offering the simplicity of controlling the form elements which assimilated "absorbed" in the CV curves, polylines, knots or wire frames. Furthermore, the most important and notable extension is that it can be connected to the machines to create the physical model “form” which can be also created in large scale by fabricating the main pieces into divided parts that can be collected on the field, this way called digital fabrication and will be discussed further in the next two chapters. The following paragraphs illustrates the bases of those digital tools and thier capabilities of creating digital forms.

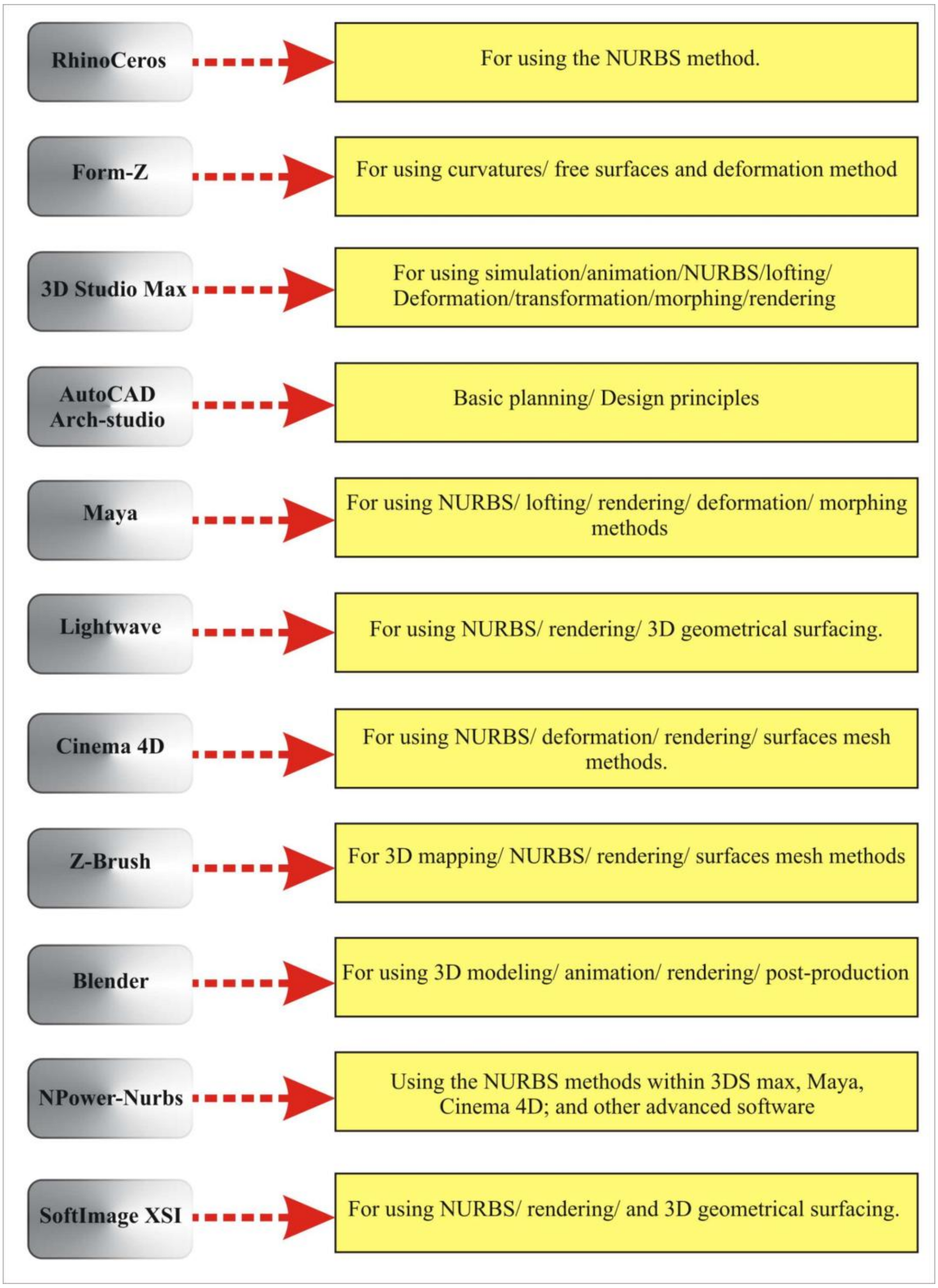


Figure 85: The most common software used to defining and creating regular and irrigular digital forms.

5.1.1 RhinoCeros

Rhinoceros is one of the most famous software which is specially made for creating free-form and three dimensional objects by using Nurbs method. The Elements of RhinoCeros can be summarized as follows:

"point, line, polyline, polyline on mesh, free-form curve, circle, arc, ellipse, rectangle, polygon, helix, spiral, conic, TrueType text, point interpolation, control points (vertices)" (Rhinoceros 3.1 index).

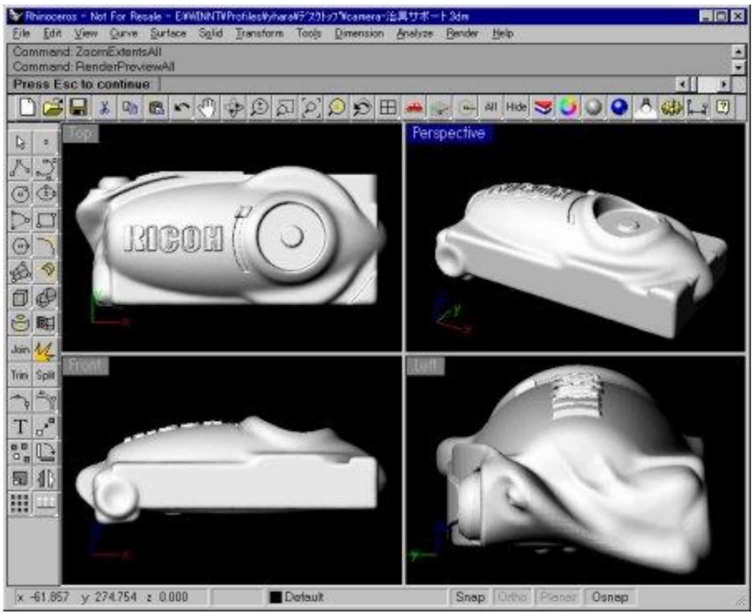


Figure 86: RhinoCeros interface

(Source: http://www.rfactory.co.jp/case/gallery/ff_cam/index02.shtml)

5.1.2. Form-Z

Form-Z is an award winning general purpose solid and surface modeler with an extensive set of 2D/3D form manipulating and sculpting capabilities, many of which are unique. It is an effective design tool for architects, landscape architects, urban designers, engineers, animators and illustrators, industrial and interior designers, and all design fields that deal with the articulation of 3D spaces and forms.

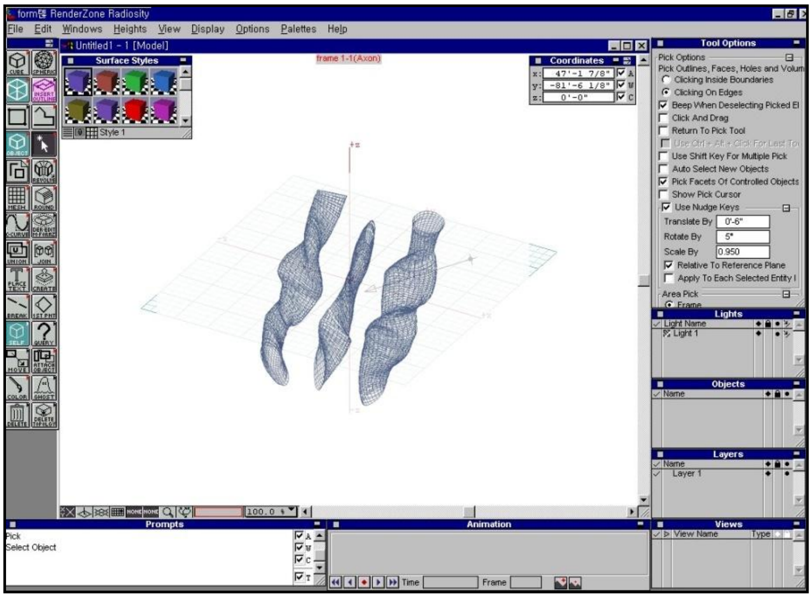


Figure 87: form-Z interface

(Source: http://babel.massart.edu/~kristinebolhuis/)

There are three kinds of objects that can be created:

- Wireframes:

  Objects are composed of lines or open polylines and cannot be rendered.

- Surface models:

  Objects are composed of closed polylines or polyline meshes (at least three edges) and can be rendered.

- Solid models:

  A set of faces that encloses space fully is a solid. Solids can be used as operands for the Boolean operations such as Union, Intersection and Difference. Form-Z does not warn before creating a bad solid. A bad solid is one that contains self intersecting faces or poorly defined faces. A poorly defined face is one that cannot be contained in a plane. Such solids are useless objects. They cannot be used in Boolean operations and create problems for rendering.

All form-Z objects "(wireframes, surfaces, and solids)" are faceted. In other words, they are composed of points, which define lines, which, in turn, define faces (Form-Z 4 index). There are no true curves or curved faces in form-Z.

5.1.3. 3D Studio MAX

Formerly known as “3D Studio”, 3ds max is a 3D modeling, animation and rendering program from the discreet division of Autodesk, Inc., San Rafael, CA (www.discreet.com). Widely used in the areas of interactive games, visual effects for movies and industrial design models, the software lets to create 2D shapes that become the cross sections of the 3D models. The application includes an animation module that uses inverse kinematics, which links components so that they move together, adding to the effect of bringing a character to life.

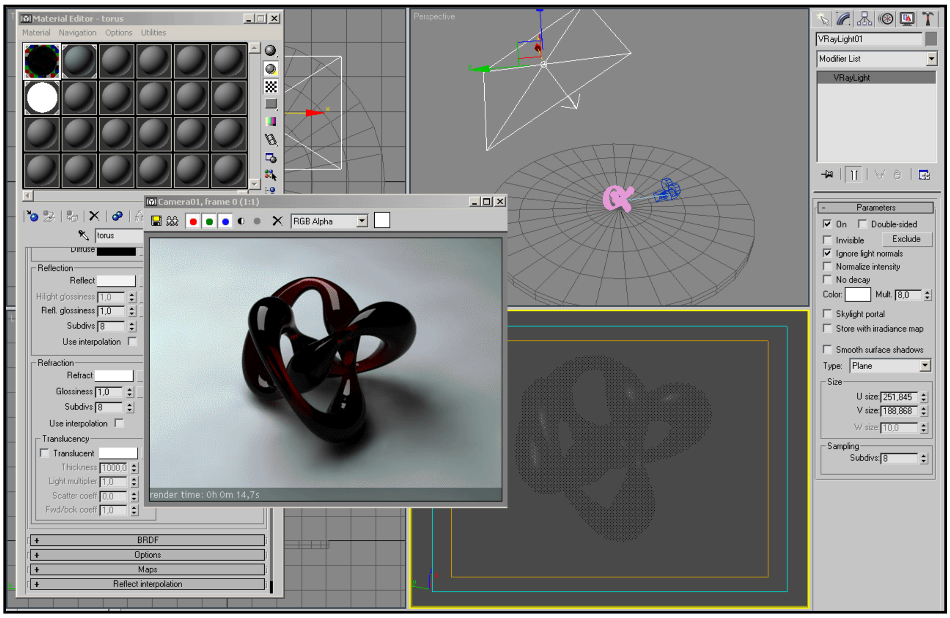


Figure 88: 3Ds Max interface

(Source: http://www.aversis.be/extra_tutorials/vray_basic_material_settings_02.htm)

The study made categorization of 3D Max elements which can be identified as follows::

- **2D tools:** Point / line / ployline / S-pline / arch / plane / circle / rectangular / ellipse / Helix / NURBS curve (Point curve & CV curve).

- 3D tools:

1.Standard primitive: - (Box / cone / sphere / geosphere / cylinder / tube /...etc

2.Extended primitive:- (torus knot / chamfer Box / spindle / ring wave /…etc

3.NURBS surfaces:- (point surf / CV surf)

- Modification methods:

Extrude / editable mesh / editable poly / editable patch / edit mesh / loft / morph / Boolean / conform / shape merge / Bend / smoothing / lattice / skin morph / slice / twist / subdivide / vertex weld / deformation / transformation.

- Animation: By controlling the key sectors and adding data coordinate

5.1.4. Autodesk Architectural Studio:

Autodesk Architectural Studio software is the design communication tool for creating, presenting, and collaborating in a single digital environment. It re-creates the tools and practices of the traditional design studio and brings them into the digital world for enhanced communication of the design ideas. Quickly sketch and model preliminary ideas with direct-input conceptual design tools like pens, markers, and erasers. Combine different media - freehand sketches, precision CAD drawings, photographs, and more - in an integrated environment to investigate and present different design options.

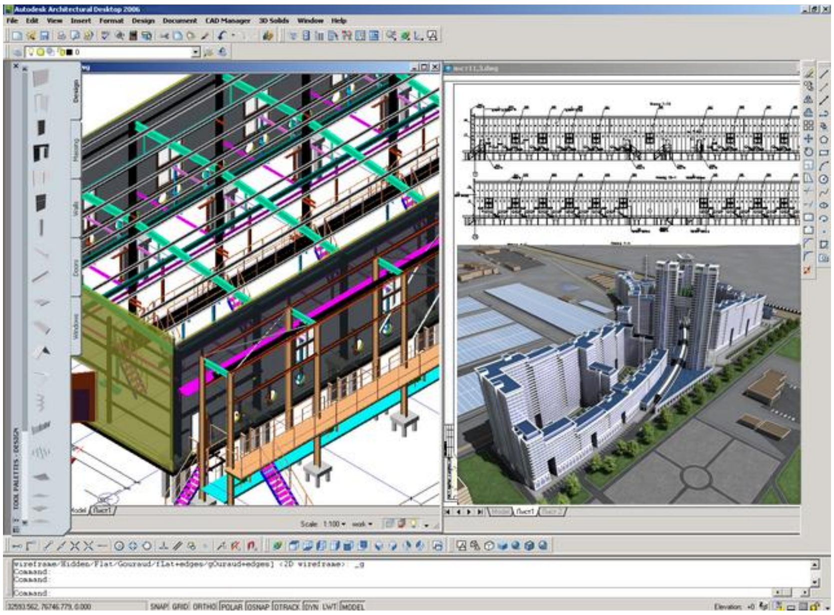


Figure 89: Autodesk architectural desktop interface.

(Source: http://www.consistent.ru/soft/version_17024.html)

5.1.5. Maya

It is software that Integrates the world's foremost modeling, animation, visual effects, and advanced rendering technologies into one complete workflow solution. It's the most comprehensive 3D software that handles massive datasets and produces professional-quality graphics on desktop PCs or graphics workstations. The study introduces the essential elements of Maya software by making the following categorization:

[Splines/ B-spline/ Curves/ NURBS/ Curvature/ Creating surfaces/ Extrude and Bevel a surfaces form a curve/ Loft/ Smoothing/ Boolean/ Bend/ Twist/ Extending/ Deformation/ Transformation/ Sculpting surfaces].

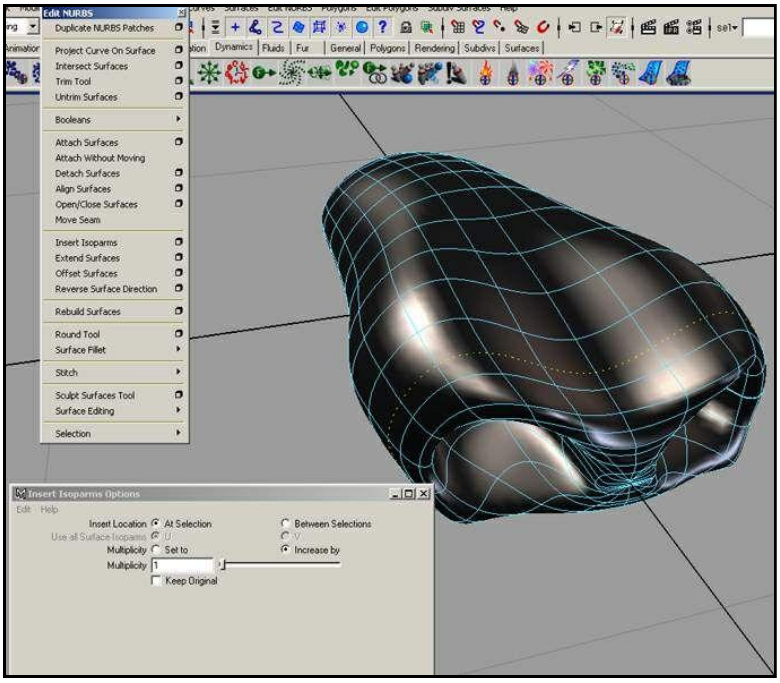


Figure 90: MAYA interface.

(Source: http://www.86vr.com/scripts/print.asp?did=9025)

The Capabilities of MAYA can be placed into several categories. The study made classification of common capabilities of Maya software as follows:

- **Modeling and Texturing**, Maya gives the access to a full suite of advanced “Polygon, NURBS and Subdivision Surface” modeling and texturing tools.
- **Animation Animators**: gain a comprehensive range of “keyframe, non-linear and advanced character animation editing tools” for creating, animating, adapting and repurposing animation data and editing realistic digital characters.
- **Visual Effects:** Dynamic interaction of “hard and soft bodies” determined by physics, as well as industry-leading particle tools and a new Toon Shader allow artists to achieve a wide range of visual effects.
- **Fluid Effects:** The simulation and rendering of a huge variety of “atmospheric, pyrotechnic, viscous liquid, and open ocean effects” overcomes one of the greatest barriers in computer animation.
- **NURBS**: Maya comes with tools for the creation, styling and rendering of fully dynamic modeling on “NURBS or polygon objects”. Includes the ability to make any NURBS curve dynamic for use in advanced character rigging and effects (Autodesk Maya 8 index).
- **Convert** a Curve or surface to non-rational geometry.

5.1.6. Lightwave

LightWave (or, more properly, LightWave 3D) is a computer graphics program for 3D modeling, rendering, and animation. Like many other 3D packages, Lightwave is composed of two parts, “an object modeling environment” where 3d models or meshes are created and “an animation environment” where models are arranged and animated for render (LightWave 8 index). The essential elements of Lightwave software can be placed as following:

[Creating primitive objects / Creating points and polygons / Creating curves / Transforming objects / Extending, duplicating and dividing objects / Surfacing objects and mapping textures / Morphing objects / Deforming objects / Animating objects / Enabling objects / Rendering]

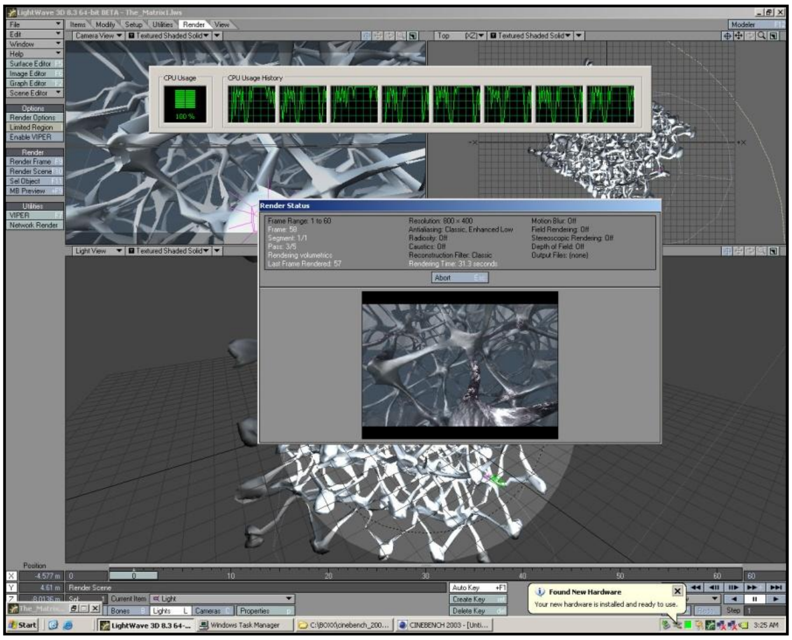


Figure 91: Lightwave interface.

(Source: http://www.digitalintermediates.com/articles/viewarticle.jsp?id=33905)

5.1.7. Cinema 4D

Cinema 4D is a popular software program relies on widely used computer 3D technology which works by creating groups of "points" (known as vertices) who form surfaces when connected. The illusion of three dimensions is created by modeling objects out of multiple surfaces. Still pictures, movies and game environments (among other things) can be created with this technique. It has also Rendering operation which refers to the act of calculating the scene, the shading, the colors and the textures. Rendering a movie is especially time-consuming - lots of images must be calculated, often with special frame-to-frame blending effect to give the animation a 'video' look. Cinema 4D capabilities can be categorized as following:

- Advanced Render
- Dynamics (for simulating soft body and rigid body dynamics)
- Sketch & Toon (tools for cell shading, cartoons and technical drawings)
- Thinking Particles (enhanced particle system based on nodes)
- Three dimension modeling with its complete sets of creation.
- Transforming any regular shapes or forms into arbitrary once.
- The ability to deforming any 2D & 3D shapes.

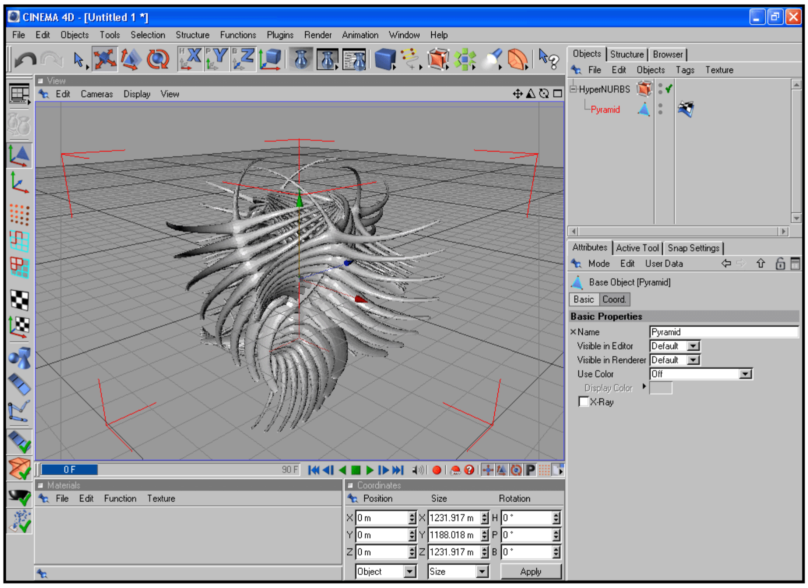


Figure 92: Cinema 4D interface.

(Source: http://www.digitalabuse.net/user-c4dabstract.htm)

5.1.8. Z-Brush

Z-Brush is one of the graphical soft wares that is professionally offers a unique and powerful blend of 2D painting with 3D sculpting, texturing, animating and rendering. The program is highly optimized to allow tremendous levels of details, both in terms of extremely high polygon counts for modeling and also for finishing scenes. The essential elements of Z-Brush can be summarized as following:

[3D objects primitives / High resolution Texturing / Displacement Creation / Curves: Modifying any type of curves without editing points / Creating irregular models and all type models type professionally / sculpting brushes / Surfacing techniques / Animating objects / High quality rendering techniques / Light effects and mapping / Superimposing the model's objects / High resolution meshes / using a skeleton-type system / Working with polygons grid / Deformation method]

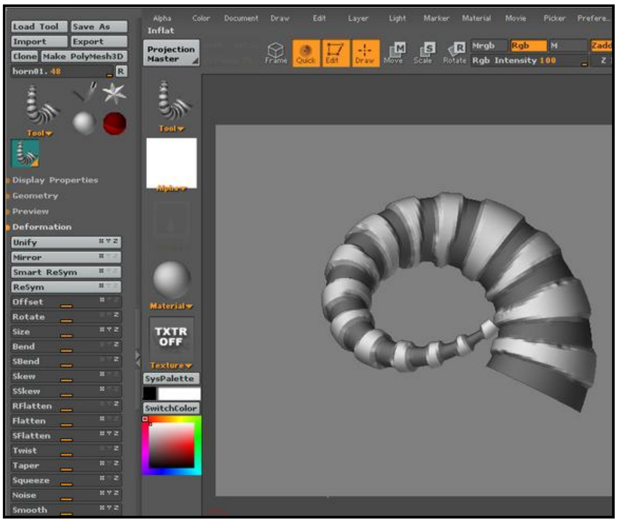


Figure 93: Z-Brush interface.

(Source: http://www.highend3d.com/zbrush/tutorials/modeling_zspheres/140.html)

5.1.8. Blender

Blender is the open source software for "3D modeling, animation, rendering, post-production, interactive creation and playback" (Blender 6 index). It creates high quality 3D graphics, movies and replay real-time, interactive 3D content. The summarized the features of Blender software as following: [Animation system / Mesh modeling / Boolean modeling tools / and Fluid dynamics tools: This deals with the integration of a free surface fluid simulation into Blender to enable the animation of liquids].

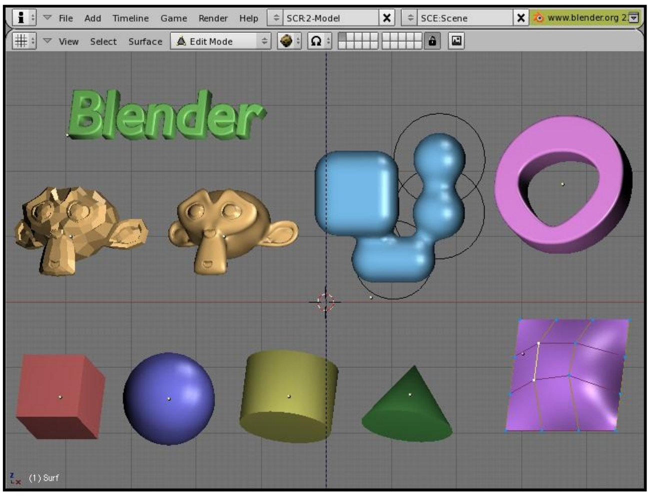


Figure 94: Blender interface.

(Source: http://www.alphachannel.com.br/page.php?menuid=203)

5.1.9. nPower-NURBS/Power solid

nPower-NURBS and Power solid are plug-ins working within 3Ds max, made by n-Power Software Company. The package considered as an innovative design creativity toolset for Autodesk 3Ds max that unifies advanced surface and solid modeling paradigms into a powerful 3D design system. It has built to bring a creative approach to building complex surfaces. nPower-NURBS lets artists work with highly precise tools in interactive, visual manner.

nPower NURBS surfaces are much more than just NURBS control point surfaces, they are defined as a procedural objects that can be recomputed whenever inputs change. There are a variety of ways that the user can control the construction or re-construction of a surface by manipulating the Power Surface Parameters. Different criteria of accuracy and knot vector creation are required for different uses. For example, automotive and aerospace design often requires "Class A" surfaces which give the highest geometric quality in terms of smoothness and continuity between surfaces.

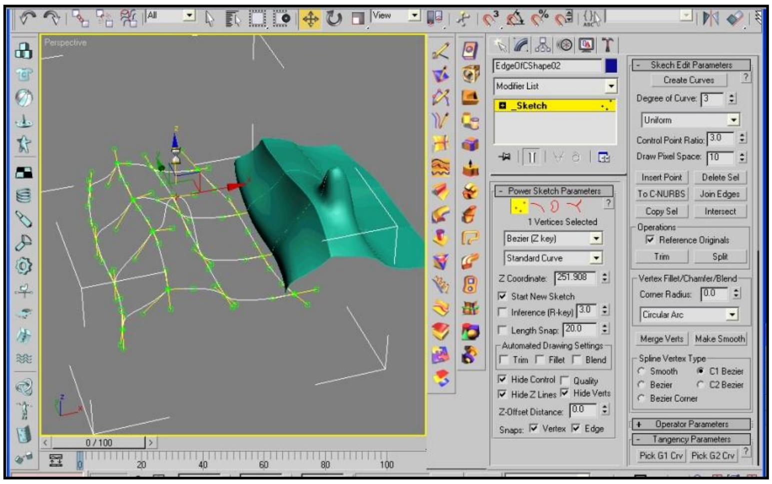


Figure 95: nPower-NURBS inside 3Ds Max.

(Source: http://www.npowersoftware.com/nurbs/pnSurfacing.htm)

Also, nPower solid is a plugging working with 3Ds max brings the powerful precision of solids modeling into the 3ds max environment and creates complex shapes using extrusions, sweeps, lofts, fillets, shelling, offsets, and precise filleting and Boolean operation. nPower Solids works with curved geometry much like

Patches. The Power Solids “Brep-Objects” can be tessellated at different levels during render time. To build up the geometry nPower NURBS and solid has several methods that can be categorized as following:

- "Class A" Surface Construction
- Extensive Surface Continuity Controls
- G2 and G3 Blending and Filleting
- Extreme Rail Sweeping Tool
- Extensive Analysis Tools
- Direct Curvature and Tangency manipulation for greater shape control with fewer curves.
- Combine Surfaces and Solids in a seamless environment
- New Technology for Blending and Sweeping to control transitions between surfaces.

5.1.11. Softimage XSI

Softimage as many graphics software has been made for creating three dimensional objects and 3D visualization. Specifically; the package dealing with the “character objects and film making”. It has been used widely among the Hollywood directors to represent their professional work. It’s based on the “advanced mapping technology, intuitive subdivision-surfaces, non-destructive character and professional rendering technique” [13].

Figure 96: Softimage XSI interface.
(Source: http://www.asilefx.com/product.php?ProductCategoryID=13&ProductID=13)

5.1.12. Essential Elelements of Digital Design Modelling

Modeling is the essential technique in digital design in which the object will be generated three-dimensionally. By the emerging of digital software it become clear that some bases in CAD have been improved to assist the process of modeling any type of complicated form. Particularly; those new bases can be identified as a new elements of CAD components such as Spline, polyline, CV curve, vertex and some other geometrical shapes that became familiar among all the designers who use the technique of computer modeling to express, generate and create any concept of form. Indeed; the diversity of these techniques may caused the difficulties of how the designer or architect can chooses the suitable once during the design process. Furthermore; the components of these techniques have not been totally identified.

For that reason the study focuses on the common modeling components that have been specifically used for creating the digital form. That's why the components of modeling software should be clearly identified to assist the designer; architect and learners for the proper way to create their concepts. The conventional components as mentioned before such as; point, line, circle, square, rectangle, and triangle …etc; has become now more flexible in the way of modeling.

Obviously, the world of digital design and modeling has many different graphical soft wares being used for modeling and expressing the design concept which proved their capabilities at this filed along the last decade. Some of these soft wares are 3D studio max, Maya, Rhinoceros, Form-Z, and others which have been discussed at the beginning of this chapter. Whereas each of them has its own manner and special abilities in the modeling and design strategy, but all using the same language.

This chapter will focus on the most common types of digital modeling elements and its definitions. The study investigates those elements and definitions through 3ds max which is one of the most common software that used for modeling or expressing any type of form.

5.1.13. Basic Definitions of Digital Modeling elements

One of the most important foundations that have been addressed in this section of the research is preliminary definition grounds based process modeling forms Unconventionality, which is one of the basics of this study. The following section will be defined the basic elements based process modeling.

5.1.13.1 Geometrical Object Primitives

Geometric primitives are basic shapes that the three dimensional software provide as parametric objects (Autodesk® 3ds Max® 9/8 index). Primitives are divided into two categories; standard primitives and extended primitives.

Geometrical Types	
Standard Primitives	Relatively simple 3D objects such as Box, Sphere, and Cylinder, as well as Torus, Plane, Cone, GeoSphere, Tube, and Pyramid.
Extended Primitives	More complex 3D objects such as a Capsule, Chamfer Box, Gengon, Spindle, Hedra, Torus Knot, and Prism.
Compound Objects	Compound objects include Scatter, Connect, ShapeMerge, Booleans, Morph, BlobMesh, and Loft. Booleans combine the geometry of two objects using union, intersection, and differente operations. Morphs are animated objects that change one geometric shape into other shapes over time. ShapeMerge lets to embed a spline shape into a geometric mesh. Loft uses shapes as cross sections along a path to produce a 3D object.
Particle Systems	Animated objects that simulate the natural effects of the object's environment like spray, snow, blizzard, and similar collections of small objects.
Patch Grids	Simple 2D surfaces ready for modeling or repairing existing meshes.
NURBS Surfaces	Analytically generated surfaces especially suited for modeling surfaces with complicated curves.
Dynamics Objects	Objects designed for use in dynamics simulations.

Table 5: Geometrical Types Definition of digital modelling elements, (Autodesk® 3ds Max® 9/8 index)

5.1.13.1.1. Standard Primitives

Geometric primitives are familiar as objects in the real world such as balls, pipes, boxes, doughnuts and Cones as shown in (figure 98). They can be modeled, improved or combined into more complex objects by changing their parameters and modifiers according to each software capabilities (Autodesk® 3ds Max® 9/8 index).

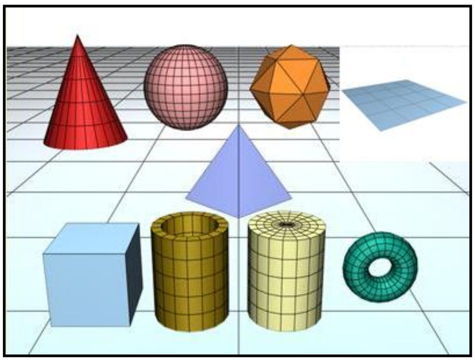


Figure 97: Collection of standard primitives, (Autodesk® 3ds Max® 9/8 index).

standard primitive objects can be converted to editable mesh objects, editable poly objects, and NURBS surfaces. Also primitives can be converted to "patch objects" (Autodesk® 3ds Max® 9/8 index). As will be extensively explained at the second part of this chapter

methods	Sub-Object Geometry details
Mesh	Vertex, Edge, Face, Polygon, Element
Poly	Vertex, Edge, Border, Polygon, Element
Spline	Vertex, Segment, Spline
Patch Surface	Vertex, Edge, Patch, Element, Handle
NURBS Curve	Curve CV or Point, Curve
NURBS Surface	Surface CV or Point, Surface

Table 6: The different between editable object creation methods, (Autodesk® 3ds Max® 9/8 index).

Classification of standard Primitive Objects:

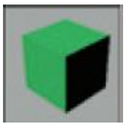
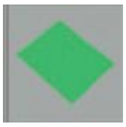
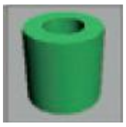
Standard Primitives Objects		Term of use 2D/3D	Parameters	Converted to method
	**Box**	**3D**	Length, Width, Height	Editable-Poly Editable-Mesh Editable-Patch NURBS
	**Sphere**	**3D**	Radius	Editable-Poly Editable-Mesh Editable-Patch NURBS
	**Geosphere**	**3D**	Radius	Editable-Poly Editable-Mesh Editable-Patch NURBS
	**cylinder**	**3D**	Radius, Height	Editable-Poly Editable-Mesh Editable-Patch NURBS
	**Cone**	**3D**	Radius1, Radius2, Height	Editable-Poly Editable-Mesh Editable-Patch NURBS
	**Pyramid**	**3D**	Width, Depth, Height	Editable-Poly Editable-Mesh Editable-Patch NURBS
	**Plane**	**3D**	Length, Width	Editable-Poly Editable-Mesh Editable-Patch NURBS
	**Tube**	**3D**	Radius 1, Radius 2, Height	Editable-Poly Editable-Mesh Editable-Patch NURBS
	**Torus**	**3D**	Radius1, Radius2	Editable-Poly Editable-Mesh Editable-Patch NURBS

Table 7: Classification of standard Primitive Objects, (Autodesk® 3ds Max® 9/8 index).

Box Primitive: Box produces the simplest of the primitives. "Cube is the only variation of Box". However, it can be varying the scale and proportion to make many different kinds of rectangular objects as shown in (figure 98), from "large, flat panels and slabs to tall columns and small blocks" (Autodesk® 3ds Max® 9/8 index).

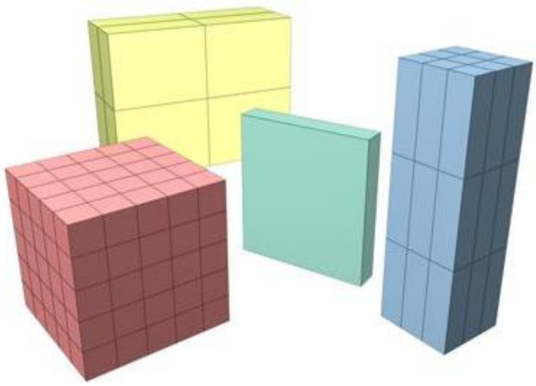


Figure 98: Examples of boxes, (Autodesk® 3ds Max® 9/8 index).

Cone primitive: The creation possibility of the cone allows "producing round cones, either upright or inverted" as shown in (figure 99) (Autodesk® 3ds Max® 9/8 index).

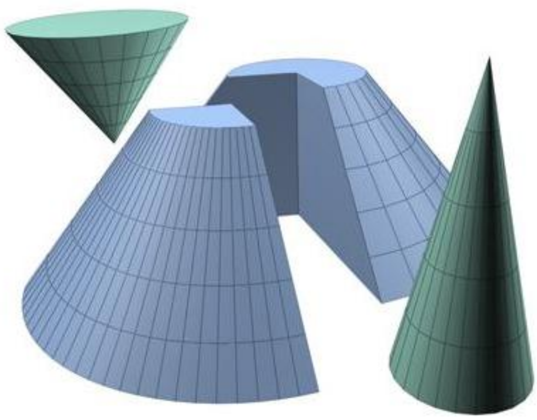


Figure 99: Cone samples, (Autodesk® 3ds Max® 9/8 index).

Sphere Primitive: It can produce a full sphere, or a hemisphere or other portion of a sphere. Also it's possible to "slice" a sphere about its vertical axis as shown in (figure 100) (Autodesk® 3ds Max® 9/8 index).

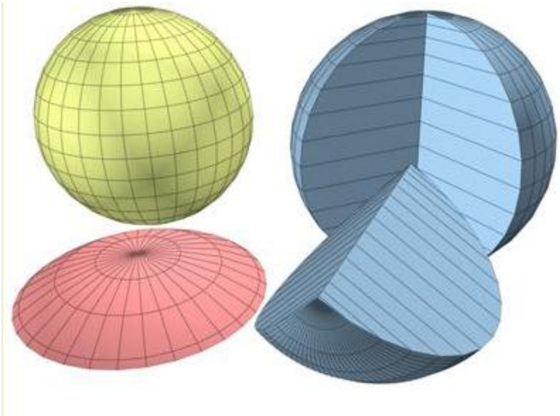


Figure 100: Examples of sphere creations, (Autodesk® 3ds Max® 9/8 index).

GeoSphere Primitive: Using GeoSphere for making spheres and hemispheres based on three classes of "regular polyhedrons", see (figure 101). "Geospheres produce a more regular surface than standard spheres. Unlike a standard sphere, a geosphere has no poles" (Autodesk® 3ds Max® 9/8 index).

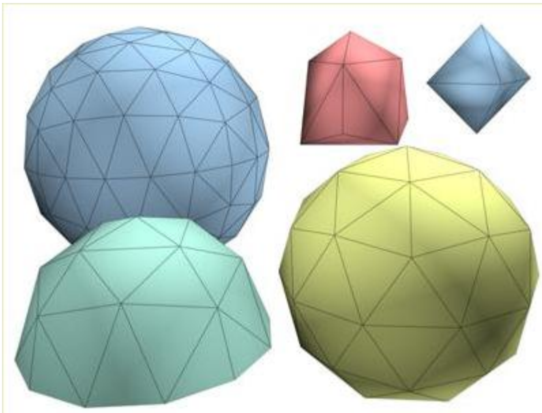


Figure 101: Examples of geospheres, (Autodesk® 3ds Max® 9/8 index).

Cylinder Primitive: Cylinder produces a cylinder that can be "slicing" around its major axis as shown in (figure 102) (Autodesk® 3ds Max® 9/8 index).

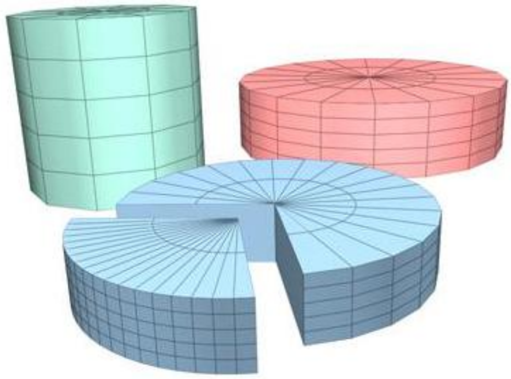


Figure 102: Cylinder examples, (Autodesk® 3ds Max® 9/8 index).

Tube Primitive: Tube produces both "round and prismatic tubes" (Autodesk® 3ds Max® 9/8 index). The tube is similar to the cylinder with a hole in it. See (figure 103).

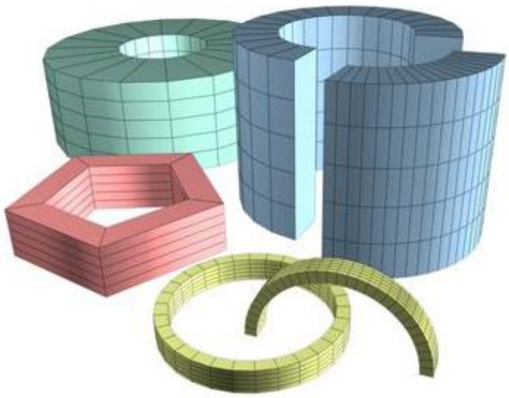


Figure 103: Tube examples, (Autodesk® 3ds Max® 9/8 index).

Torus Primitive: Torus produces "a torus, or a ring" with a circular cross section, sometimes referred to as "a doughnut" (Autodesk® 3ds Max® 9/8 index). It can be combined three smoothing options with rotation and twist settings to create complex variations. See the (figure 104).

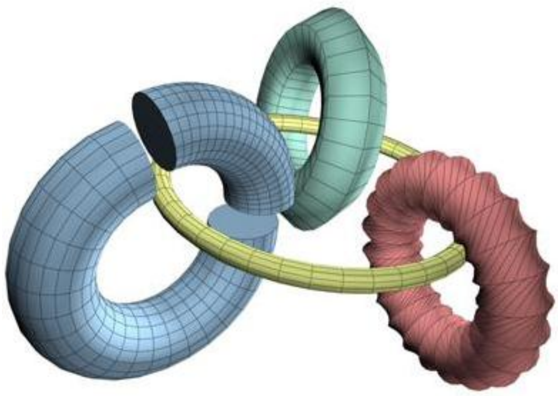


Figure 104: Examples of Torus, (Autodesk® 3ds Max® 9/8 index).

Pyramid Primitive: The Pyramid primitive has a “square or rectangular base and triangular sides” (Autodesk® 3ds Max® 9/8 index). See the (figure 105).

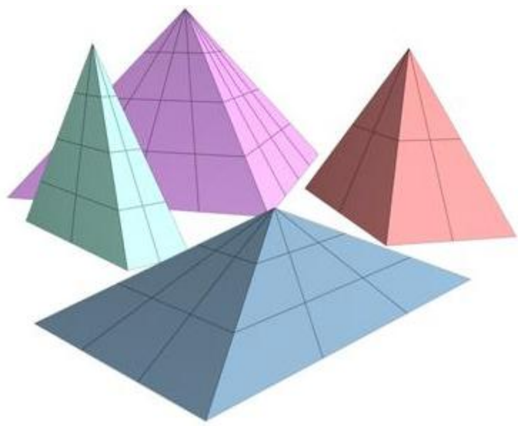


Figure 105: Examples of pyramids, (Autodesk® 3ds Max® 9/8 index).

Plane Primitive: The Plane object is a special type of “flat polygon mesh” that can be enlarged by any amount. It can be specifying factors to “magnify the size or number of segments, or both” as shown in (figure 106) (Autodesk® 3ds Max® 9/8 index).

Figure 106: plane example, (Autodesk® 3ds Max® 9/8 index).

5.1.13.1.2. Extended Primitives:

Extended Primitives are "a collection of complex primitives for the 3d world" as sown in the (figure 107) (Autodesk® 3ds Max® 9/8 index). The section and table that follow describe each type of extended primitive and creation parameters.

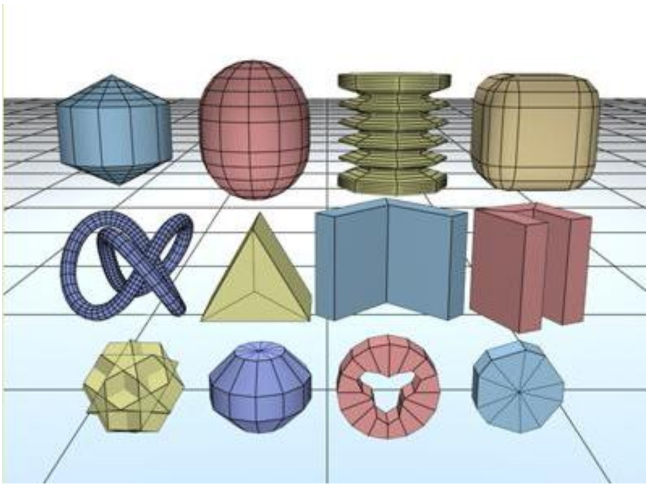


Figure 107: A collection of extended primitive objects, (Autodesk® 3ds Max® 9/8 index).

Classification of Extended Primitive Objects:

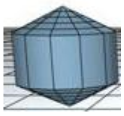
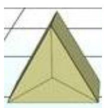
Extended Primitives Objects	Term of use	Parameters	Converted to method
 **ChamferBox**	**3D**		Editable-Poly Editable-Mesh Editable-Patch NURBS
 **Hedra**	**3D**		Editable-Poly Editable-Mesh Editable-Patch NURBS
 **Torus Knot**	**3D**		Editable-Poly Editable-Mesh Editable-Patch NURBS
 **Capsule**	**3D**		Editable-Poly Editable-Mesh Editable-Patch NURBS
 **Spindle**	**3D**		Editable-Poly Editable-Mesh Editable-Patch NURBS
 **Gengon**	**3D**		Editable-Poly Editable-Mesh Editable-Patch NURBS
 **Prism**	**3D**		Editable-Poly Editable-Mesh Editable-Patch NURBS

Table 8: Classification of Extended Primitive Objects, (Autodesk® 3ds Max® 9/8 index).

ChamferBox Extended Primitive: Using ChamferBox "to create a box with beveled or rounded edges" (figure 108) (Autodesk® 3ds Max® 9/8 index).

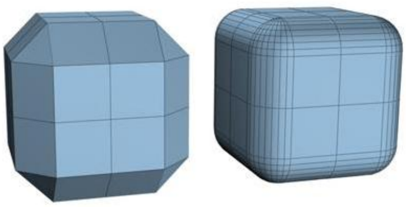


Figure 108: Chamfer-Box beveled or rounded edges, (Autodesk® 3ds Max® 9/8 index).

Hedra Extended Primitive: Using Hedra is to produce objects from several families of “polyhedra” as in (figure 109) (Autodesk® 3ds Max® 9/8 index).

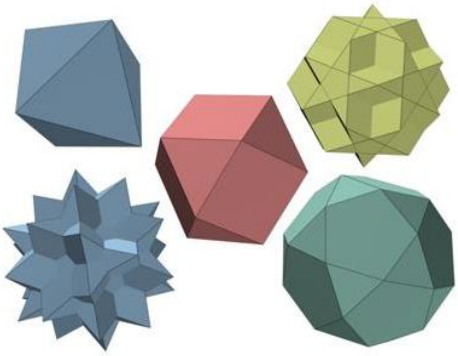


Figure 109: Hedra examples, (Autodesk® 3ds Max® 9/8 index).

Torus Knot Extended Primitive: Using “Torus Knot” to create a complex or “knotted torus” by drawing 2D curves in the normal planes around a 3D curve. The 3D curve (called the Base Curve) can be either a circle or a torus knot. A torus knot object can be converted to “a NURBS surface” (figure 110) (Autodesk® 3ds Max® 9/8 index).

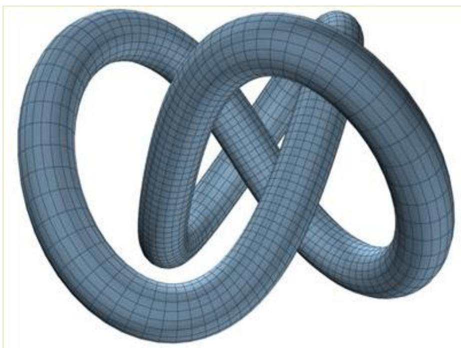


Figure 110: Torus Knot example, (Autodesk® 3ds Max® 9/8 index).

Capsule Extended Primitive: Using Capsule to create “a cylinder with hemispherical caps” (figure 111) (Autodesk® 3ds Max® 9/8 index).

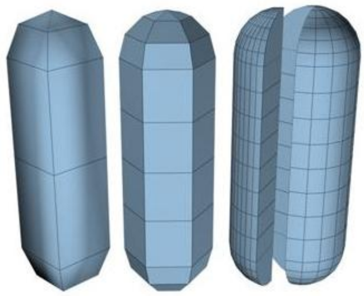


Figure 111: Capsule examples, (Autodesk® 3ds Max® 9/8 index).

Spindle Extended Primitive: Using the Spindle primitive to create "a cylinder with conical caps" (figure 112) (Autodesk® 3ds Max® 9/8 index).

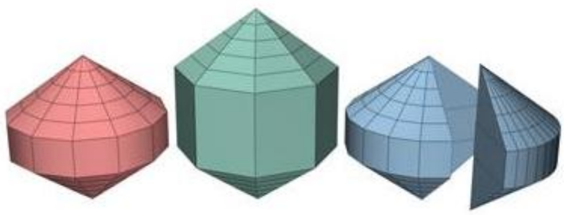


Figure 112: Spindle extended examples, (Autodesk® 3ds Max® 9/8 index).

Gengon Extended Primitive: Using Gengon to create an extruded, regular-sided polygon with optionally filleted side edges (figure 113) (Autodesk® 3ds Max® 9/8 index).

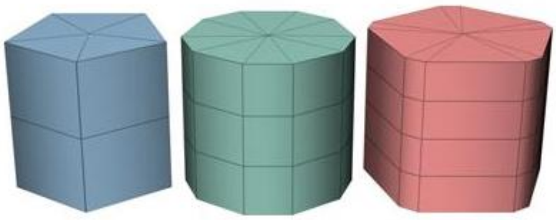


Figure 113: Gengon extended examples, (Autodesk® 3ds Max® 9/8 index).

Prism Extended Primitive: Using Prism to create "a three-sided prism with independently segmented sides" as shown in (figure 115) (Autodesk® 3ds Max® 9/8 index).

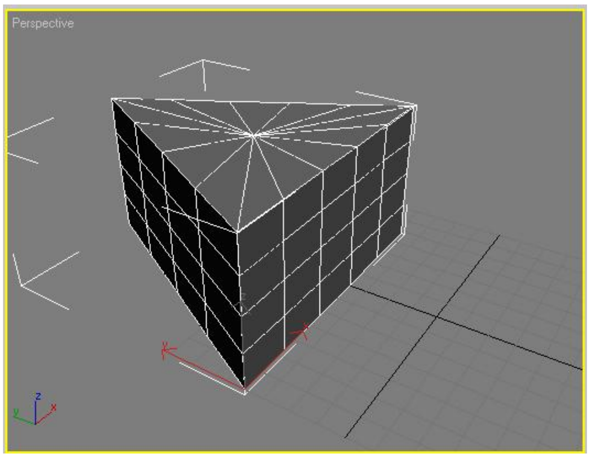


Figure 114: Prism extended example, (Autodesk® 3ds Max® 9/8 index).

Compound Objects: Compound objects generally combine two or more existing objects into a single object. For instance; "standard primitive objects and extended primitive objects can be combined together for each group" (Autodesk® 3ds Max® 9/8 index). Some types of compound objects as follows:

Scatter Compound Object: Scatter is a form of compound object that "randomly scatters the selected source object either as an array, or over the surface of a *distribution* object" (figure 115) (Autodesk® 3ds Max® 9/8 index).

Figure 115: Results of scattering source object with distribution object, (Autodesk® 3ds Max® 9/8 index).

BlobMesh Compound Object: The BlobMesh compound object creates "a set of spheres from geometry or particles", and connects the spheres together as if they were made of a "soft, liquid substance" (Autodesk® 3ds Max® 9/8 index). When the spheres move within a certain distance of one another, they connect together. When they move apart, they take on a spherical form again. As shown in (figure 116).

Figure 116: Blobmesh Compound object sample of liquid, (Autodesk® 3ds Max® 9/8 index).

In the 3D industry, the general term for spheres that operate in this way is "*metaballs"*. The BlobMesh compound object "generates metaballs based on specified objects in the scene, and the metaballs, in turn, form a mesh result called a *blobmesh"* (Autodesk® 3ds Max® 9/8 index). A blobmesh is ideal for simulating thick liquids and soft substances that move and flow when animated.

Metaballs: A type of object that joins itself to other objects with a connecting surface. "When one metaball object moves within a certain distance of another, a connecting surface is formed between the two" (Autodesk® 3ds Max® 9/8 index).

Shape-Merge Compound Object: Shape-Merge creates a compound object consisting of a mesh object and one or more shapes. The shapes are either "embedded in the mesh, altering the edge and face patterns, or subtracted from the mesh" (figure 117) (Autodesk® 3ds Max® 9/8 index).

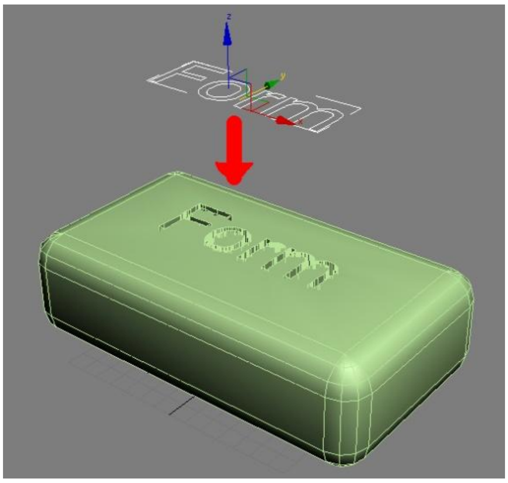


Figure 117: An example of how two objects can be projected into one, (Autodesk® 3ds Max® 9/8 index).

Boolean Compound Object: A "Boolean object combines two other objects by performing a Boolean operation on them" (Autodesk® 3ds Max® 9/8 index). The Boolean operations on geometry can be categorized as follows:

Union: - The Boolean object contains the volume of both original objects. The intersecting or overlapping portion of the geometry is removed as shown in (figure 118).

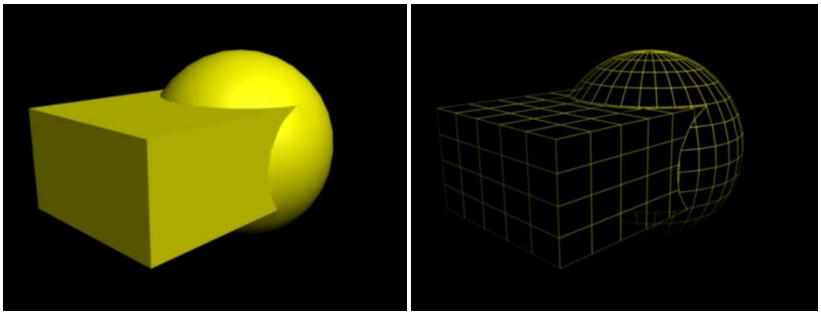


Figure 118: Example of two objects Union.

Intersection: - The Boolean object contains only the volume that was common to both original objects. in other words, where they overlapped. See figure (119).

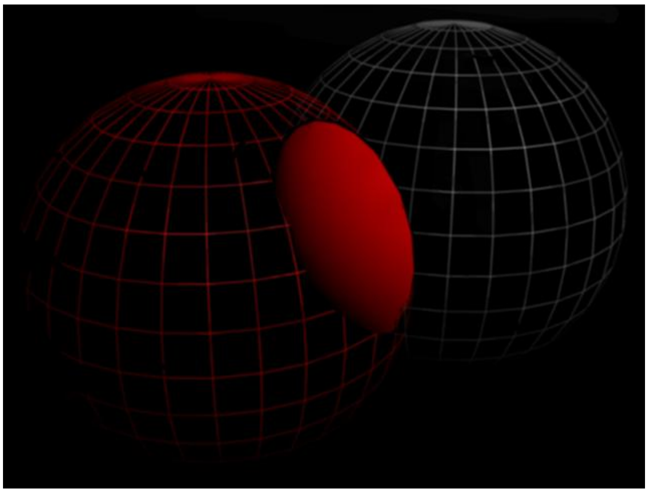


Figure 119: Intersecting two object

Subtraction (or difference):- The Boolean object contains the volume of one original object with the intersection volume subtracted from it as can be seen in figure (120).

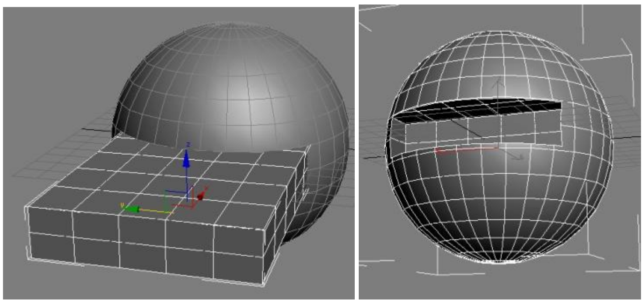


Figure 120: The two objects intersected then the subtracted object created.

Particle Systems:

Particle systems are useful for a variety of animation tasks. Primarily, they're employed when animating a large number of small objects using procedural methods; for instance, creating a "snowstorm, a stream of water, or an explosion". The three dimensional software provide two different types of particle systems: "event-driven and non-event-driven". The event-driven particle system also known as "particle Flow", "tests particle properties", and, based on the test results, sends them to different events. Each event assigns various attributes and behaviors to the particles while they're in the event. In the non-event-driven systems, particles typically "exhibit similar properties throughout the animation" (Autodesk® 3ds Max® 9/8 index).

And there are several way to create particle systems such as "Spray Particle System, Snow Particle System, Super Spray Particle System, Blizzard Particle System, PArray Particle System, PCloud Particle System". One example of these techniques which can be used to create sophisticated object explosions is "PArray Particle System" as shown in (figure 121) (Autodesk® 3ds Max® 9/8 index).

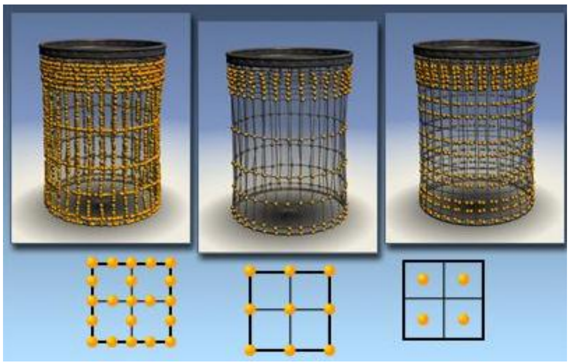


Figure 121: presenting how particles can be distributed on an object, (Autodesk® 3ds Max® 9/8 index).

Patch Grids: From one of the most remarkable graphic software 3ds max which identify the patch grids that can create two kinds of patch surfaces in grid form: "Quad Patch and Tri Patch". Patch grids begin as flat plane objects but can be modified into arbitrary 3D surfaces by either using an Edit Patch modifier. Furthermore, it can be converting a basic patch grid to an "editable patch object" (figures 122, 123) (Autodesk® 3ds Max® 9/8 index).

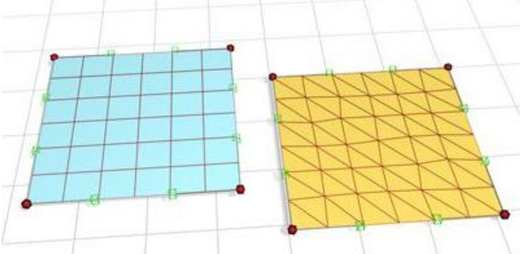


Figure 122: patch grid basic objects, (Autodesk® 3ds Max® 9/8 index).

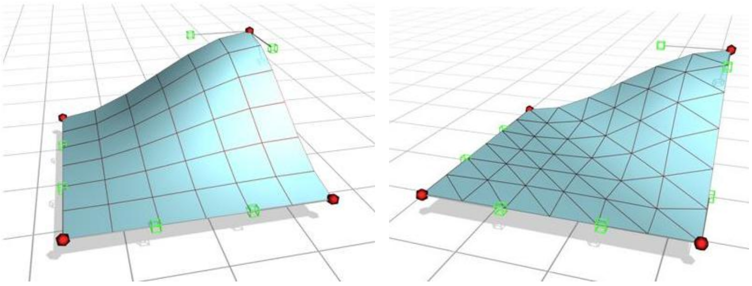


Figure 123: Quad Patch and Tri Patch, (Autodesk® 3ds Max® 9/8 index).

Dynamics Objects: Dynamics is “a branch of physics that describes how objects move. Dynamic animation uses rules of physics to simulate natural forces”. By specifying the actions required and the object to take, then let the software figure out how to animate the object. Dynamic animation lets to create realistic motion that's hard to achieve with traditional key-frame animation. For instance, it can be made some effects such as “tumbling, waving flags, breathing and explosion. Etc" (Autodesk® MAYA® 8 index).

Dynamics objects are similar to other “mesh objects”, except that they can be made to react to the “motion” of objects to which they are bound, or they can provide “dynamic forces” when included in a “dynamics simulation” (Autodesk® 3ds Max® 9/8 index). In short, Particle objects, soft bodies, and rigid bodies are dynamic objects.

5.1.13.2. Geometrical Shape Primitives

Geometrical shape primitives is the essential elements of digital design drawing and modeling that forms the main skeleton of an object to be exist in three-dimensional coordinate. Consequently; geometrical shape types can be categorized as follows:

Geometrical Shape Types	
B-Splines	Common 2D shapes such as Point, Line, Rectangle, Circle, Ellipse, Arc, Donut, also Helix but it’s a 3D shape
NURBS Curves	A Point Curve and CV Curve provide the starting points for complex surfaces.

Table 9: Geometrical shape types, (Autodesk® 3ds Max® 9/8 index).

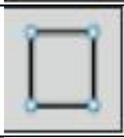
Shape primitive Types		The Term of use	Converted to method	Shape details
	**line**	2D	Editable-Spline NURBS	First and end points And it can has some vertexes in between
	**Rectangle**	2D	Editable-Spline NURBS	Four corner and the corner can be curved
	**Circle**	2D	Editable-Spline NURBS	Radius and it has four vertexes
	**Ellipse**	2D	Editable-Spline NURBS	Two radius and it has four vertexes
	**Arc**	2D	Editable-Spline NURBS	Two end points and center point
	**Donut**	2D	Editable-Spline NURBS	Two circle with four vertex
	**NGon**	2D	Editable-Spline NURBS	Tangent points with vertexes
	**Helix**	3D	Editable-Spline NURBS	Spiral around an axis

Table 10: Shape primitive types, (Autodesk® 3ds Max® 9/8 index).

B-Splines: In the computer science subfields of computer-aided design and computer graphics the term "B-spline frequently refers to a spline curve parameterized by spline functions that are expressed as linear combinations of B-splines" [14]. Briefly, B-Spline is a type of free lines that has several points attached with tangents at certain points for controlling the line shape called "vertex" which can be controlled freely to define the structure of any irregular shapes.

Line: The line primitive includes several creation methods enabling to create hard sharp corners or smooth sharp corners. The strategy of the drawing by line "Spline" is by defining the first and the end point of the line; also some several points can be added in between so they'll called "vertexes" which help to control the main desired shape. Furthermore; the shape can be converted to the advanced methods to become 3D form (Autodesk® 3ds Max® 9/8 index).

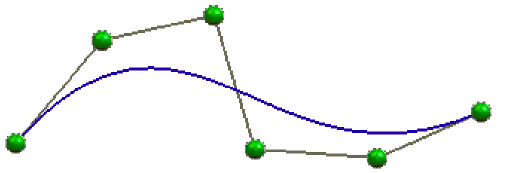


Figure 124: B-splines elements defined by the first, second points and vertexes.
(Source: http://en.wikipedia.org/wiki/Basis_B-spline)

Rectangle: The rectangle shape produces simple rectangles by specifying the length and the width; also a corner radius.

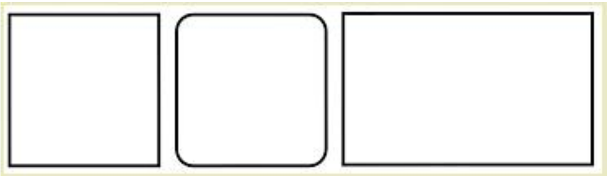


Figure 125: Rectangle samples, (Autodesk® 3ds Max® 9/8 index).

Circle: The circle as common can be produced by adjusting the radius and it has only four vertexes.

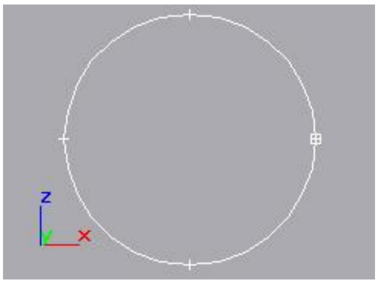


Figure 126: circle sample, (Autodesk® 3ds Max® 9/8 index).

Ellipse: Ellipses are simple variations of the circle shape. It can be defined by length and width values; or it can be produced by using the circle shape and adjusting the control points of the four vertexes.

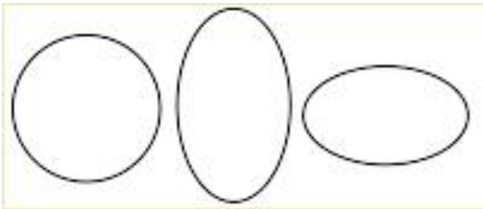


Figure 127: Ellipse samples, (Autodesk® 3ds Max® 9/8 index).

Arc: The Arc primitive has two creation methods. The first one by specifying the two end points; and the second one by defining the center to one of the end points then specifying the Arc length then the shape will be completed.

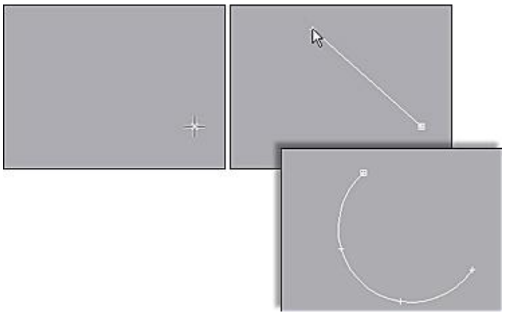


Figure 128: Creating Ellipse by specifying two end points, (Autodesk® 3ds Max® 9/8 index).

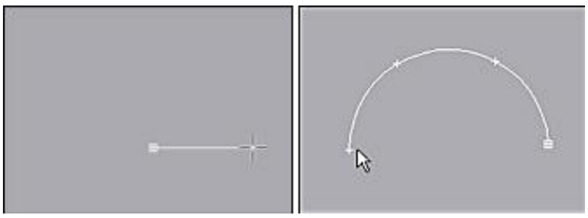


Figure 129: Creating Ellipse by defining the center to one of the end points and the Arc length, (Autodesk® 3ds Max® 9/8 index).

Donut: As another variation of the circle shape, the Donut shape consists of two concentric circles; it can be created by specifying the outer and inner circle.

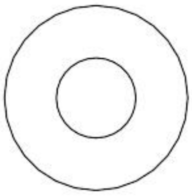


Figure 130: Donut sample, (Autodesk® 3ds Max® 9/8 index).

NGon: The NGon shape “regular polygon” can be created by specifying the number of sides and the corner radius; also it can be specifying that whether the “NGon is inscribed or circumscribed” as can be seen in the (figure 131) (Autodesk® 3ds Max® 9/8 index).

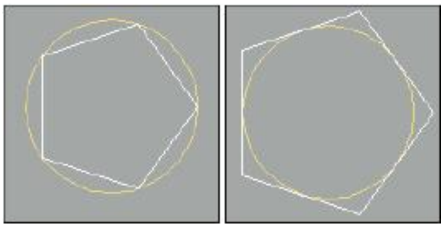


Figure 131: An inscribed pentagon and a circumscribed pentagon, (Autodesk® 3ds Max® 9/8 index).

“Inscribed polygons” are positioned within a circle that touches all the outer polygon’s “vertexes”. Whereas “circumscribed polygons” are positioned outside of a circle that touches the midpoint of each “polygon edge” (Autodesk® 3ds Max® 9/8 index).

Helix: Helix is like a “spring coil shape”; and it is the only shape of all the shape primitives that exists in 3D coordinates. Helix parameters include two radii for specifying the inner and outer radius. These two values can be equal parameters also exist for the height and number of Turns. The bias parameter causes the “Helix turns to be gathered all together at the top or bottom of the shape” (Autodesk® 3ds Max® 9/8 index). The (figure 132) shows a sampling of *Helix* shapes.

Figure 132: The Helix shape can be straight or spiral shaped, (Autodesk® 3ds Max® 9/8 index).

NURBS curves: There are two kinds of NURBS curve objects that can be categorized as following:

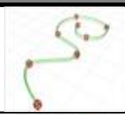
Types of NURBS curves		The term of use	Converted to method
	**Point Curve**	**2D/3D**	**Editable mesh NURBS**
	**CV Curve**	**2D/3D**	**Editable mesh NURBS**

Table 11: Types of NURBS Curves Objects, (Autodesk® 3ds Max® 9/8 index).

Point Curve: Point curves are "NURBS curves" whose points are constrained to lie on the curve. A point curve can be the "basis of a full NURBS model" (Autodesk® 3ds Max® 9/8 index).

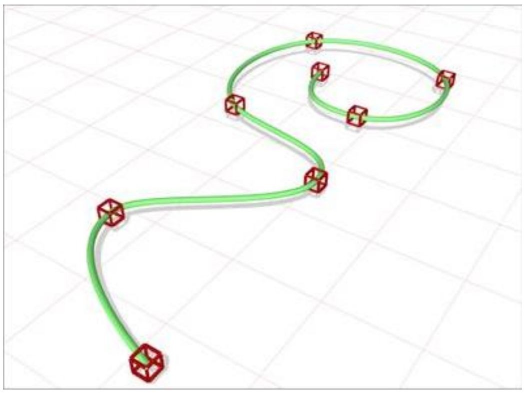


Figure 133: Point curve lie on the curve they define, (Autodesk® 3ds Max® 9/8 index).

CV Curve: CV curves are "NURBS curves controlled by control vertices (CVs)". The CVs don't lie on the curve. They define "a control lattice" that encloses the curve. Each CV has a "weight" that can be adjusted to change the curve (Figure 134) (Autodesk® 3ds Max® 9/8 index).

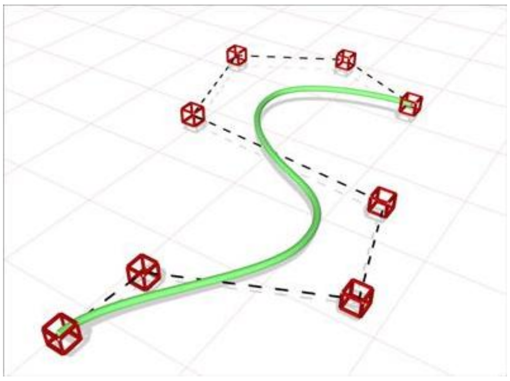


Figure 134: CVs shape the control lattice that defines the curve, (Autodesk® 3ds Max® 9/8 index).

5.2. HARDWARE: (Digital fabrication tools)

New developments in the field of Computer-Aided Design and Manufacturing (CAD/CAM) have impacted the automotive, aerospace and marine industries. Along with the development of digital technologies and the fabrication techniques, digital tools are increasingly adapted in architectural design. Because of the involvement of digital tools, the design process has been greatly affected; in other words, digital tools liberated the confines of forms and structuring of architectures.

Digital Fabrication is a part of the design process where a design description is translated into a physical representation using rapid prototyping devices. Digital Fabrication is the junction between design, computation and rapid prototyping, each field loaded with many overlapping interest and advanced possibilities. For instance; digital fabrication tools allow for the physical manufacturing of ideas using computers and machines that transforming the process of design from being just thought or drawing to be physically existed. During this part the study trying to explore the procedures of using digital fabrication tools during the construction process to bridging the gap between design concept and actual production, seeking to investigate today's design paradigms on the potential production of digital design and manufacturing techniques in architecture.

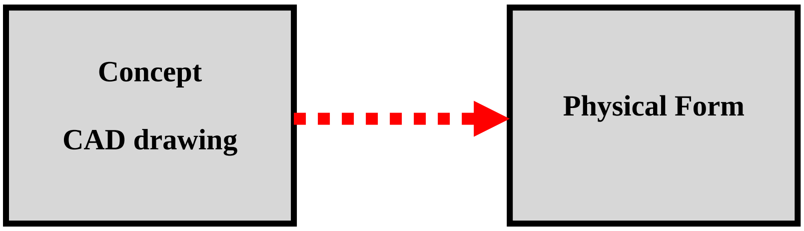


Figure 135: The logic of digital fabrication.

Thirty years ago, Researchers began contemplating the “automatic model shop” (William M. Newman and Robert F. Sproull, 1979) when they became aware of the possibilities provided by computer-aided milling machines (figure 137). In 1977, Mitchell wrote that by “interfacing production machinery with computer graphics systems, a very sophisticated design/production facility can be developed” (W. J. Mitchell, 1977).Technology progressed, by the 1990’s there was an extensive body of research conducted by Bernd Streich at the Department of CAAD and Planning Methods at the University of Kaiserslautern in Germany. He wrote numerous papers and a book on the topic of computer-aided techniques for fabricating physical models. In 1991 he introduced the use of stereolithography, one of the “only RP techniques available then, as a feasible method for building architectural models” (Seely, Jennifer C.K. and Sass, Larry. 2004). In 1996 he wrote a book titled “Computer-gestützter Architekturmodellbau” [Computer-Aided Architectural Model Building], which was the first complete work to describe the topic of “digital fabrication in the architectural design process” (Bernd Streich,1996).

Alvise Simondetti’s 1997 Master’s thesis, titled “Rapid Prototyping in Early Stages of Architectural Design” addressed how digital fabrication could be used to make architectural models (Alvise Simondetti, 1997). In his thesis, Alvise teaches the reader 25 frequent mistakes made by a designer when he or she attempts to use these technologies. In 2002, researchers in the Rapid Design and Manufacturing Group at the Glasgow School of Art published a paper discussing the “applicability of RP techniques in the field of architecture” (Gerard Ryder, et al, 2002).

Even more recently, Breen, et al. at the Delft University of Technology published an article describing how “CNC milling machines, laser cutters, and three-dimensional printers” can be utilized in the architectural model-making process (Jack Breen, Robert Nottrot, and Martijn Stellingwerff, 2003). Since then, these digital fabrication machines have found their way into even more schools and offices. As these machines become more common in the field, designers, professors, and researchers are exploring “new methods of designing, teaching, and working with digital fabrication” (Bechtold, Martin, Kimo Griggs, Daniel L. Schodek, and Marco Steinberg, ends, 2003). Now that designers have had the chance to integrate these fabrication processes into their model building techniques. Thus, the study trying to investigates these new technology and their effects on the production process.

Figure 136: Physical model of object constructed from computer model with numerically controlled machine.

(Source: http://iot-ito.nrc-cnrc.gc.ca/facilities/other_mm_e.html)

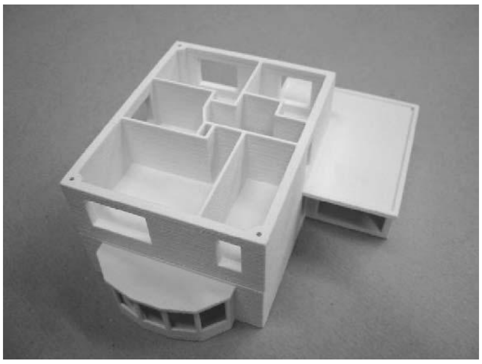


Figure 137: 3D printed house (scale 1:100) from plaster-based powder, (Automation in Construction, 2003)

Briefly, digital fabrication tools can be grouped into two categories according to the process of production. Firstly; rapid prototyping machines (layer-by-layer) which are specifically for making an experimental model or any type of small scale pieces or sculptures also known as (RP) machines. Secondly; computer numerical control machines also known as (CNC) machines which are the cutting and milling machines that prepare the final parts of the desired form into real scale once. The study investigates those machines from the early history of their discovery to the classification of their use.

5.2.1. Growth of Digital Fabrication Tools

Numerical control (NC) machines for use in 2D cutting operations were first developed at MIT in the 1950s. These early models were controlled by paper tape or punch card programs generated using a computer. They allowed parts to be manufactured in far more complexity that the most skilled craftsman. In the 1960's and 1970's specialized software was developed to translate digital drawings into NC machine specific machine paths. The use of computers with these machines became known as Computer Numerical Control (CNC).

CNC machines have a long history of use for large scale manufacturing. However, it was only in the early 1990's that CNC devices started to be used on a small scale, in design studios to develop concept models, and prototypes of "larger scale manufactured products" (Seely, Jennifer C.K. and Sass, Larry. 2004). The machines which print forms in an additive manner are called rapid prototyping machines. They were developed to build small scale physical models in one piece. Rapid prototyping and CNC machines are commonly referred to as digital fabrication tools.

5.2.2. Digital Fabrication Machines

As mentioned digital fabrication tools (Hardware) can be grouped into two categories: Computer Numerical Control Machines (CNC) and Rapid Prototyping Machines (RP). Due to the diversity of digital machines that have been used in different fields such as industrial, mechanical engineering and so on; the study classified the types which have been tested in the field of architecture both for making physical models and producing large scale parts.

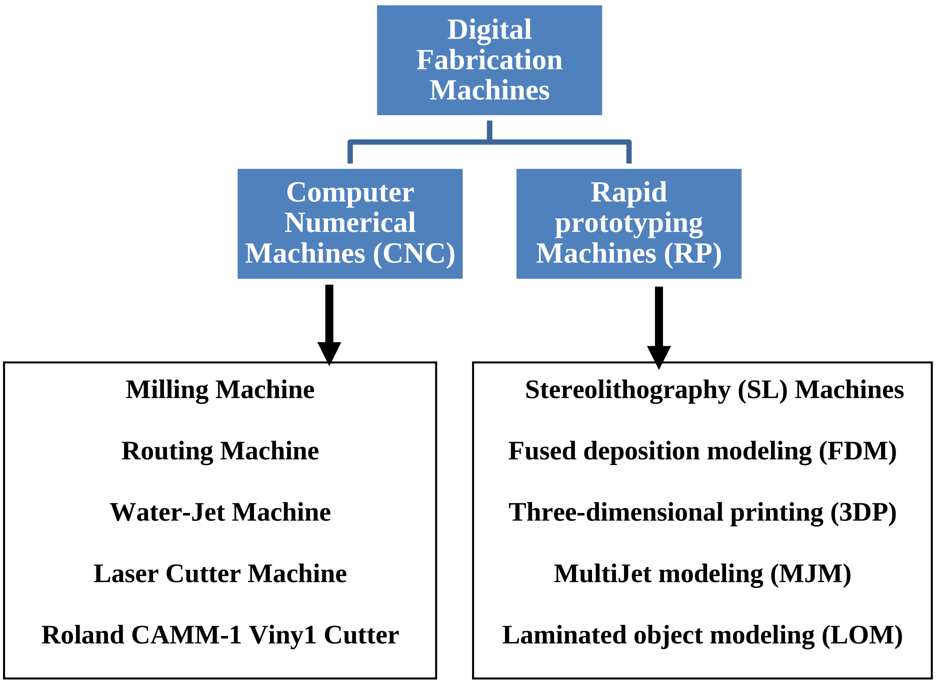


Figure 138: Categories of Digital Fabrication Machines.

5.2.2.1. Computer Numerical Control (CNC) Machines

The term "CNC machining" refers to the process of Computer Numerical Controlled Machining, where machines cut materials under the control of computer processors. This process typically allows parts to be manufactured which are very accurate and very complex. It also allows parts to be machined very quickly, repeatedly and tends to be quite flexible. The study attempts to briefly sum up the most common types of “CNC machines” oprations that mostly used in physical modelling and digital production.

5.2.2.1.1. CNC milling machines

CNC milling is used to create forms from blocks of materials such as woods, metals, plastics, and foams. These machines come in a variety of sizes. The MIT Department of Architecture has two desktop CNC milling machines, the Roland Modela MDX-20 (figures 140, 141) and the Denford Micromill 2000 (figure 142). Another one also at the industrial-sized HAAS Super Mini Mill milling machine (figure 143)-(Seely, Jennifer C.K. and Sass, Larry. 2004). This fabrication tool is most useful for creating small, singular architectural components.

Figure 139: Roland Modela MDX-20 desktop milling machine, (Seely, Jennifer C.K. and Sass, Larry. 2004).

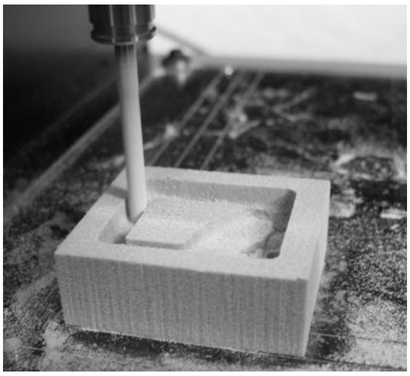


Figure 140: Rigid foam being milled on the Modela MDX-20milling machine, (Seely, Jennifer C.K. and Sass, Larry. 2004)

Figure 141: Denford Micromill 2000 desktop milling machine, (Seely, Jennifer C.K. and Sass, Larry. 2004)

Figure 142: HAAS Super Mini Mill, (Seely, Jennifer C.K. and Sass, Larry. 2004)

5.2.2.1.2. CNC Routing Machine

A similar digital fabrication tool is CNC Routing, which works in a similar fashion to milling except it is meant to "cut large, flat, sheet materials versus smaller, block materials" (figure 143). Many architecture schools have table routers, such as the Precix 9100 in their shops due to the router's applicability in creating large site models or other complex forms from materials such as "large plywood or foam sheets" (Seely, Jennifer C.K. and Sass, Larry. 2004).

Figure 143: Precix Industrial Series 9100 4'x8' table router, (Seely, Jennifer C.K. and Sass, Larry. 2004)

5.2.2.1.3. CNC waterjet Machine

CNC waterjet machining is also used to cut large, flat sheets of material. An advantage; the waterjet cutter has over the table router is the "wide spectrum of materials" it can cut. In addition to plywood and foam, it can cut "metal, stone, glass, rubber, composite materials", and many more. An example of these machines is the "OMAX 2652 waterjet cutter" (figures 144,145) (Seely, Jennifer C.K. and Sass, Larry. 2004).

Figure 144: OMAX Waterjet Machining cutter,
(Seely, Jennifer C.K. and Sass, Larry. 2004)

Figure 145: Waterjet cutting example.

(Source: http://www.woodlandmanufacturing.com/water-jet-cutting.html)

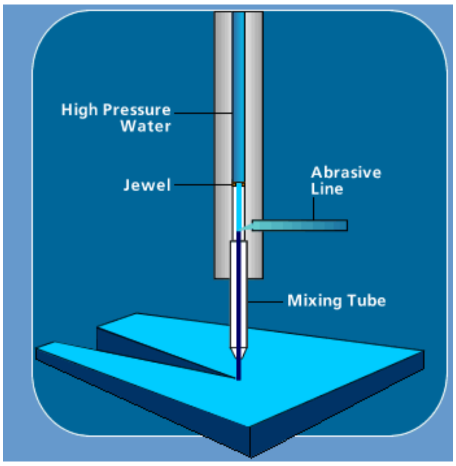


Figure 146: Waterjet cutting detail

(Source: http://www.newaterjet.com/faq.html)

5.2.2.1.4. Laser cutters Machines

Like CNC milling machines, laser cutters also come in a variety of sizes, ranging from desktop to shop-sized machines. The MIT Department of Architecture has a Universal Laser Systems “X-660 laser cutter” (figure 147), which can cut sheets of material up to “5.5m x 9.8m”. Universal Laser Systems also provides desktop laser platforms that are cheaper and more suitable for small offices. Laser cutters typically cut thin, sheet materials such as “wood, paper, chipboard, museum board, cardboard, foam-board, and plastics” (figure 148) (Seely, Jennifer C.K. and Sass, Larry. 2004).

Figure 147: Universal Laser Systems X-660 Laser Platform,
(Seely, Jennifer C.K. and Sass, Larry. 2004)

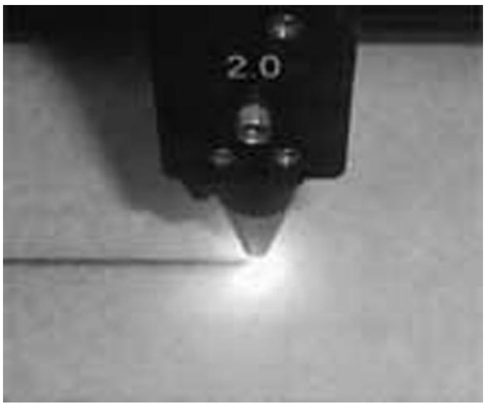


Figure 148: Laser cutting example,
(Seely, Jennifer C.K. and Sass, Larry. 2004)

5.2.2.1.5. Roland CAMM-1 vinyl cutter

The fifth CNC machine is the Roland CAMM-1 vinyl cutter, which cuts very thin sheets of "vinyl, paper, acetate, and foil" with a small blade (figure 149). Creating "precise, smooth cuts" is its greatest advantage (figure 151) (Seely, Jennifer C.K. and Sass, Larry. 2004). Many other CNC processes exist; however, the five that have been mentioned are the most useful in the architectural design process. CNC plasma cutting, wire cutting, turning, and turret punching are some of the many other processes currently available. The prices of CNC machines currently run between $2,000 and $500,000.

Figure 149: Roland CAMM-1 vinyl cutter,
(Seely, Jennifer C.K. and Sass, Larry. 2004)

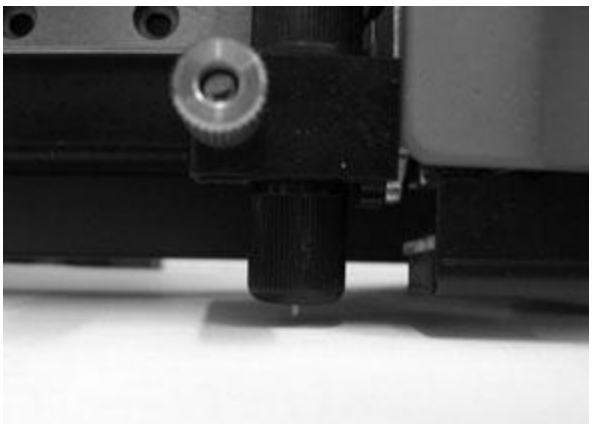


Figure 150: Roland CAMM-1 vinyl cutter,
(Seely, Jennifer C.K. and Sass, Larry. 2004)

Figure 151: CNC plasma cutter machine.

(Source: http://www.mat-cut.com/en/machines_decoupe.htm)

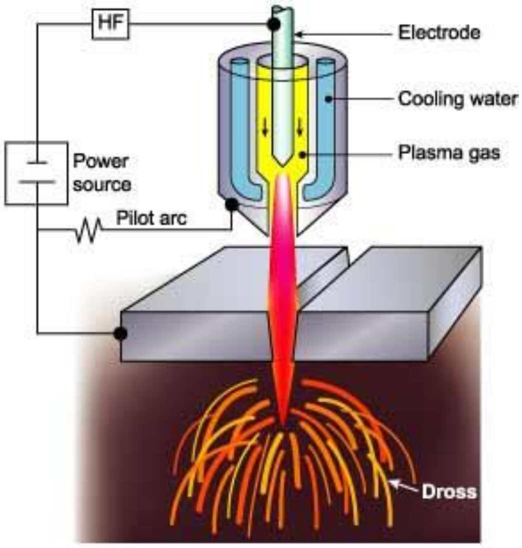


Figure 152: CNC plasma cutting process.

(Source: http://www.mat-cut.com/en/machines_decoupe.htm)

5.2.2.2. Rapid Prototyping (RP) Machines

The term “rapid prototyping” (RP) refers to a class of technologies that can automatically construct physical models from Computer-Aided Design (CAD) data. These "three dimensional printers" allow designers to quickly create tangible prototypes of their designs, rather than just two-dimensional pictures. The Rapid Prototyping or “RP” of related digital technologies are also known by the names additive fabrication, three dimensional printing, solid freeform fabrication and layered manufacturing. The study beirfly attempts to illustrate the types of these system and how they could be used in physical manufacturing and form production.

5.2.2.2.1. Stereolithography (SL) Machine

During the stereolithography (SL) process, a laser draws a layer of the desired object on the top surface of a “photosensitive liquid resin”, curing the top surface (figures 154, 155). Following each writing of a layer-by-layer process, the support surface holding the solidified resin moves down one layer’s thickness at a time, recoating the top surface with liquid resin and the next layer is written on the top surface again. A “light matrix” of material must also be “drawn” under protruding parts of the objects in order to support them during the printing. In the end, the models are made out of a very durable, transparent resin. 3D Systems’ stereolithography was “the first RP process to be commercialized, starting in 1988” (figures 153) (Seely, Jennifer C.K. and Sass, Larry. 2004), [15].

Figure 153: Stereolithography (SLA) machine.
(Source: http://www.stereolithography.com/)

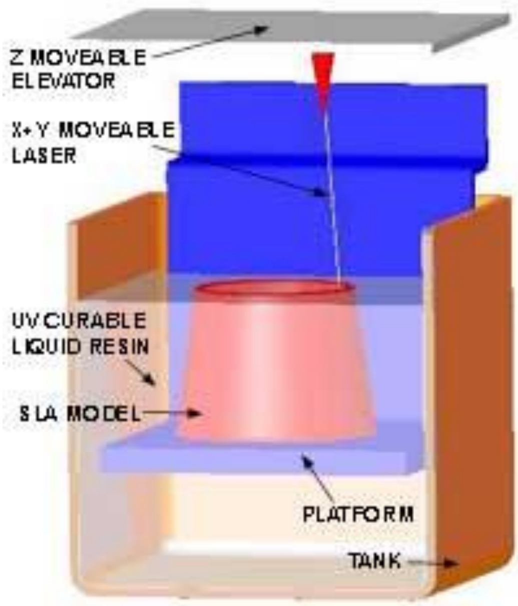


Figure 154: Stereolithography printing Process.

(Source: www.toolcraft.co.uk)

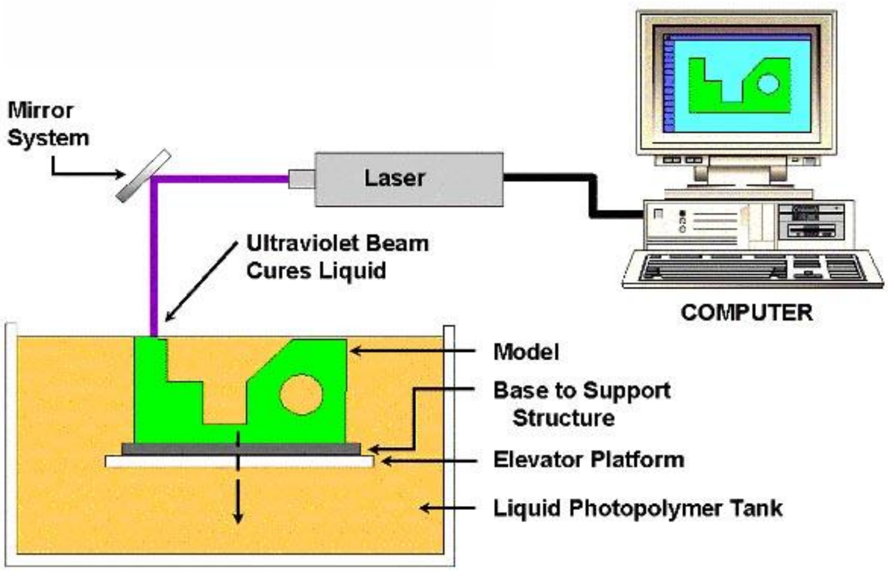


Figure 155: Stereolithography system.

(Source: http://www.rpc.msoe.edu/cbm/about/sla.php)

The sequence of "steps for producing a Stereolithography (SLA) model" is shown in the following figure [16]:

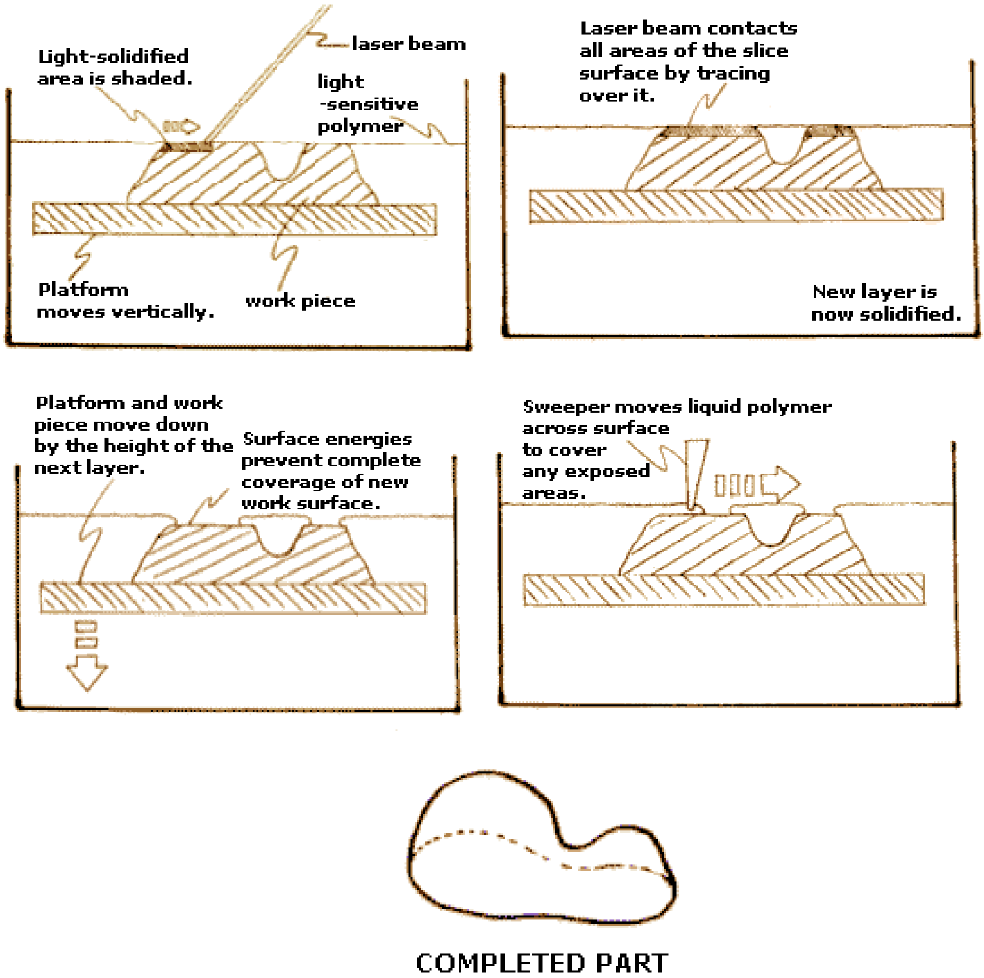


Figure 156: making model by Stereolithography Process.

(Source: http://www.efunda.com/processes/rapid_prototyping/sla.cfm)

5.2.2.2.2. Fused deposition modeling (FDM) Machine

Fused deposition modeling (FDM) has been commercialized since 1991 (figure 157). This machine "draws one layer of the desired object at a time with molten plastic". When a layer is complete the "bed moves down" and the next layer is drawn upon the previous one. Support material is drawn where needed throughout the process, as in stereolithography (figure 158, 159). The final models are made of a fairly strong "ABS plastic" (Seely, Jennifer C.K. and Sass, Larry. 2004). The MIT Department of

Architecture currently owns a Stratasys FDM 2000; however the newest FDM machine on the market today is the Dimension 3D printer.

Figure 157: Fused Deposition Modeling (FDM).
(Source: http://flickr.com/photos/garyfixler/31106922/)

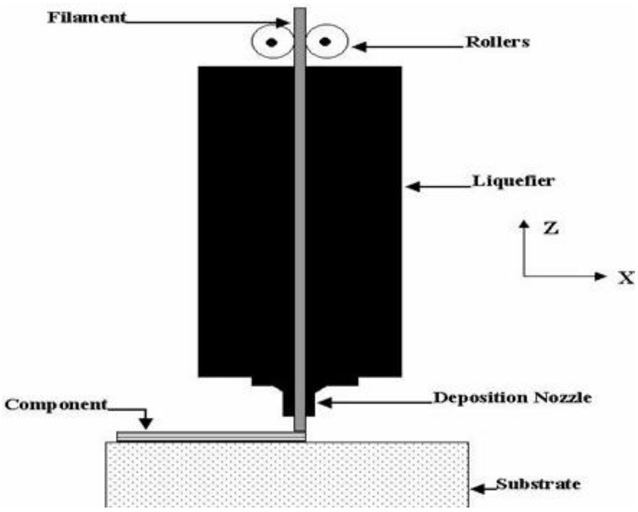


Figure 158: FDM machine components.
(Source: http://www.3d-cam.com/services/fdm.asp)

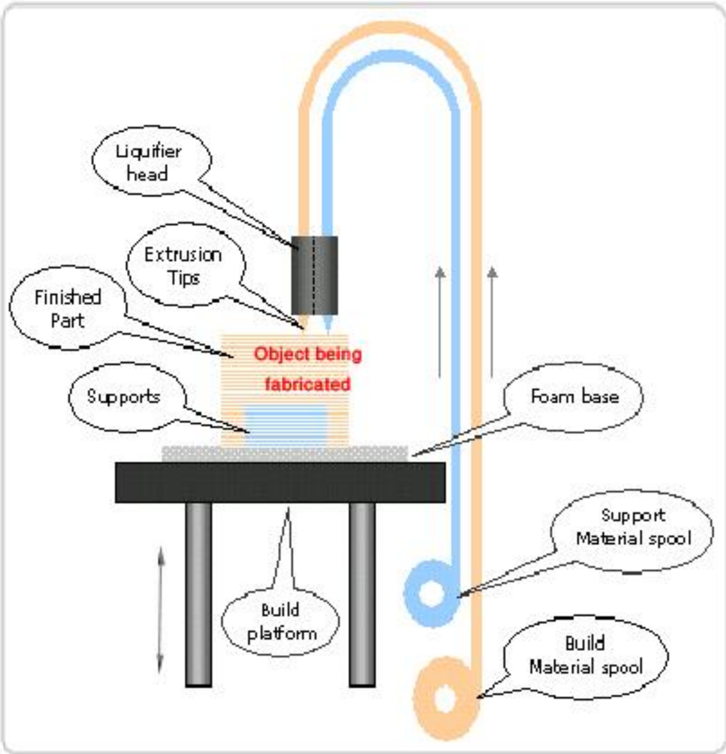


Figure 159: How FDM (**Fused Deposition Modeling)** process works.
(Source: http://www.arptech.com.au/fdmhelp.htm)

5.2.2.2.3. Three-dimensional printing (3DP)

"Three-Dimensional Printing - A Tool for Solid Modeling" was presented and officially "published" at the April 1991 Conference of the National Computer Graphics Association [17]. Three-dimensional printing (3DP) is rapidly working its way into the architectural design process more so than any other RP method. Z Corporation which produces 3DP machines has released more compact 3D printers such as “Z400 3D printer and the Z-Printer 310” that can also print color (figure 160). An inkjet-like printing head prints an entire layer of a given object with a “water-based binding fluid” on the top surface of a bed of “fine, starch- or plaster-based powder”. When the first layer of printing is done, the bed moves down, a thin layer of the “powder is spread over the freshly printed layer”, and the printing head repeats the process until the object is complete (figure 161, 162). The “non-printed powder” in the bed acts as “the support material for the print”. In the end, the models are made out of a “brittle, plaster-like material. Finishing requires blowing off excess powder and lightly curing the outside surface with some sort of binding fluid or hot wax" (Seely, Jennifer C.K. and Sass, Larry. 2004).

Figure 160: Z Corporation ZPrinter 310,
(Seely, Jennifer C.K. and Sass, Larry. 2004).

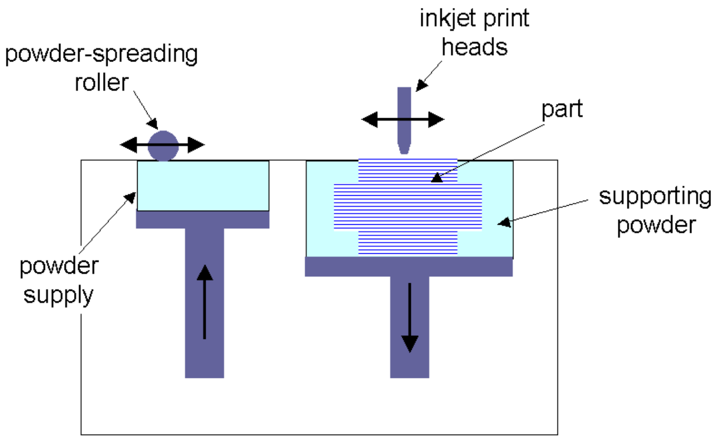


Figure 161: 3D printing machine components
(Source: http://www.architectural-model.com/3dp-history.htm)

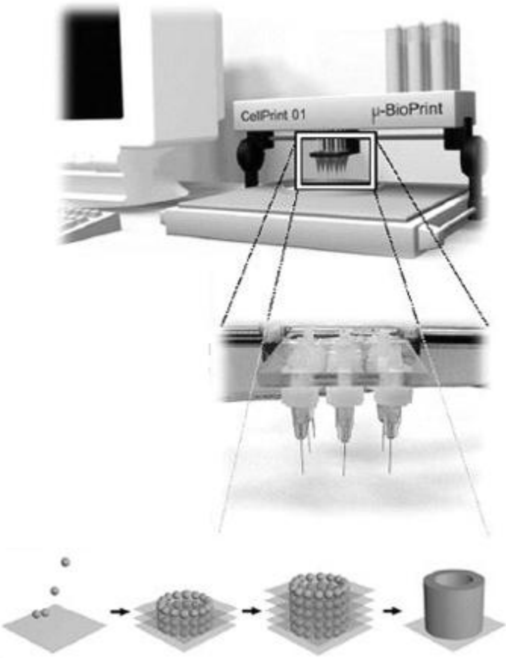


Figure 162: 3D printing machine strategy.

(Source: http://www.architectural-model.com/3dp-history.htm)

Figure 163: some different models made by Z Corp (Z510) 3D printer

(Source: http://flickr.com/photos/garyfixler/31106922/)

5.2.2.2.4. MultiJet modeling (MJM) Machine

Also similar to an inkjet printing, multiJet modeling (MJM) "prints with a head releasing tiny drops of melted, opaque wax to create the print". Each time a layer is completed the bed moves down and the next layer is printed until the object is completed (figures 164, 165). MJM is found occasionally in architecture schools and was introduced to the market in 1999. MJM machines include "3D Systems" in Version of 23D Printer and Thermojet Printer" (Seely, Jennifer C.K. and Sass, Larry. 2004).

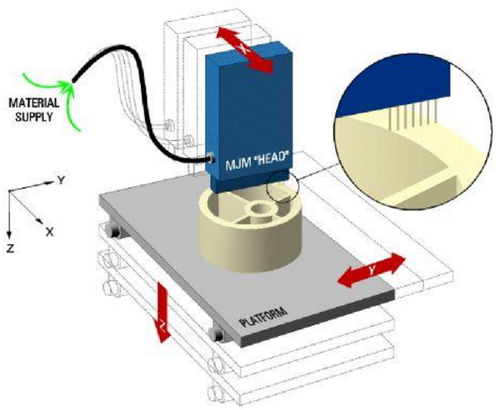


Figure 164: MJM machine details.

(Source: http://www.warwick.ac.uk/atc/rpt/Techniques/3dprinting.htm)

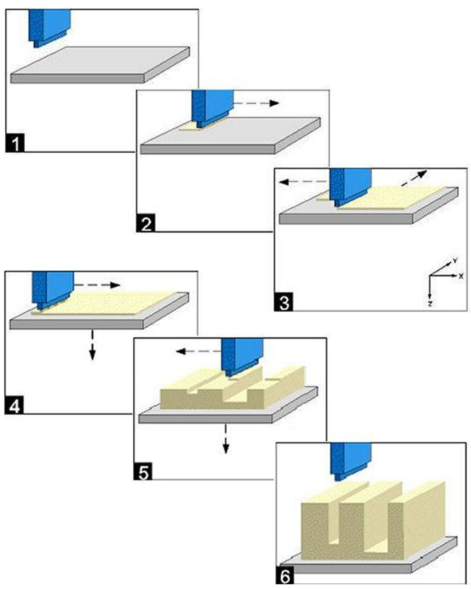


Figure 165: MJM machine process.

(Source: http://www.warwick.ac.uk/atc/rpt/Techniques/3dprinting.htm)

5.2.2.2.5. Laminated object modeling (LOM) Mahcine

The laminated object modeling (LOM) process creates objects by "repeatedly laminating thin sheets of paper, plastic, or composites". Each layer has a profile cut into it by a laser or blade, and is laminated to the previous layer. The remaining material is used as support material (figure 166). LOM has been commercialized since 1991 and currently appears to be the least utilized process compared to the SL, FDM, 3DP, and MJM processes. Many variations of these technologies and other RP processes exist, but are not used in architectural model making mainly due to high costs. Some of these other processes are "laser sintering, laser generation, and selective inhibition of sintering" (Seely, Jennifer C.K. and Sass, Larry. 2004). The prices of rapid prototyping machines currently run between $20,000 and $900,000.

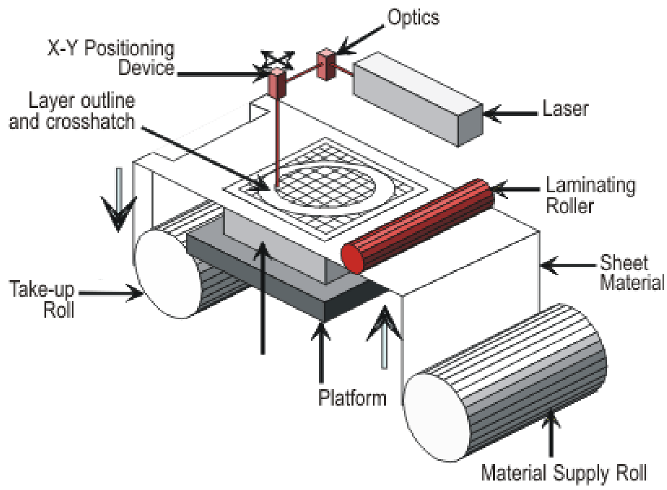


Figure 166: LOM Machine components
(Source: www.azom.com)

In this system the model is formed from successive layers of heat bonded sheet material, typically paper. The sliced CAD data is used to control a laser which cuts the perimeter (only) of each slice in the sheet material. A typical LOM machine is illustrated below (figure 167).

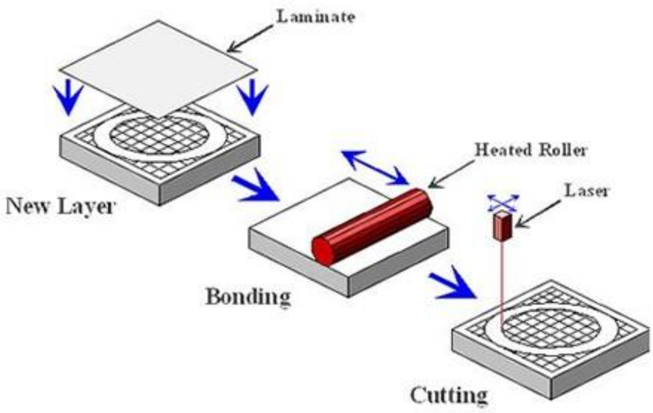


Figure 167: LOM process of modeling.
(Source: http://www.warwick.ac.uk/atc/rpt/Techniques/lom.htm)

As can be seen above, once each layer is complete a new sheet of material is heat bonded on top of it and the laser cuts the next slice. The final model has the appearance of soft wood.

5.2.3. Importance of Digital Fabrication Machines

The introduction of CNC machines radically changed the manufacturing industry as well as improving the production process in architecture. Curves are as easy to cut as straight lines, complex 3D structures are relatively easy to produce. With the increased automation of manufacturing processes with computer numerical control machining (CNC) and rapid prototyping (RP), considerable improvements in consistency, quality and accuracy have been achieved. Also, they allow for more flexibility in the way parts are held in the fabrication process and solving the problem of "time consuming" which is very important for the designers and firms during the production process [18]. Simply; by the use of digital computer technology, construction methods have gradually become a product of computerized techniques, and Computers are not just used in graphical stages of design production, but are used in every step of the construction process. Using many new techniques, such as "CAD/CAM" (computer Aided design & computer aided manufacturing), "CNC" (computer numerical control) and "RP" (Rapid prototyping), the form in architecture has reached an entirely new level which leads the designers to handle complicated form (Mitchell, 1998 a; Kloft, 2001; Ruby, 2001; De Luca and Nardini, 2002; Ham, 2003).

5.2.4. Accessibility of Digital Fabrication Technology

As the thesis aimed to explain the role of digital technology in both the design process and production process, the study investigates that why most of digital fabrication tools could not be easily available for use in the making of architectural models as well as in the production stage so long as those technology leads to the far improvement in architectural experiments. The availability of those tools could improve the design studio for encouraging the student's talents as well as for the offices to explore and representing their concepts realistically as some people still have more skeptical views about the ability of digital technology in the construction process, also they don't believe that the complicated type of form could be physically produced today. Thus; the study investigates the use of digital technology in education and offices in the case of design and production process to find out what kind of beneficial and difficulties they had.

In her thesis "Digital Fabrication in the Architectural Design Process", Seely, Jennifer C.K has found some critical points about using digital fabrication tools among some schools and offices in United States. Those points can be summarized as follows:

In Education, rapid prototyping technologies "can not be available at every school except for very few schools that have obtained those technologies incorporated in their teaching program". On the other hands; many types of these technologies can be found at "MIT" (Massachusetts Institute of Technology) which is the American technical college that offers the opportunities for students to having access to these technologies at little or no cost for practicing their works. The students learn to "integrate these technologies into their design processes" which improving their design explorations. In fact; the difficulty was that because of the large amount of students attending to access the "lab studio of MIT" which reduced the time limit for completing their works and prevent the others from having access to the studio (Seely, Jennifer C.K. and Sass, Larry. 2004).

In offices, architectural design offices and professionals, firstly they are "not allowed" to having access to these technologies "as freely as the students" since it is considerably more "expensive to do so out side of an academic college". on the other hands; a few rare firms exist, such as" Morphosis, California, that own their own laser cutter and/or 3D printer". Architects at Morphosis design their projects primarily in the computer through the use of 3D digital models. The 3D printer is a natural extension of such a process and they find it is "cheaper than outsourcing 3D printing to outside parties" (Seely, Jennifer C.K. and Sass, Larry. 2004). In the other side; a lot of architectural offices and firms don't incorporated those technologies in their design process because of the high cost, so they outsourcing their completed works to some special companies who have digital machines for both three-dimensional modeling or prefabrication of large scale unites. To find out how much the digital machines cost, it would be useful to sum up the prices of those new technologies. Bellow are the prices of all the digital fabrication machines mentioned so far, plus a few others that are useful for the architecture community.

Company	**Technology**	**Model**	**Price (US$)**
3D systems	SLA	SLA250/30A SLA250/40 SLA250/50 SLA350/10 SLA500/40	99.000 145.000 170.000 380.000 490.000
Stratasys	MJM FDM	Actua 2100 FDM 1650 FDM 2000 FDM 8000	65.000 125.000 160.000 200.000
Helisys	LOM	LOM1015 Plus LOM2030H	92.000 255.000
DTM Crop	SLS	Sinterstation 2000 Sinterstation 2500	300.000 400.000
Sanders prototype	DODI	ModelMaker-6Pro ModelMaker-II	59.000 65.000
Cubital	SGC	SGC 4600 SGC 5600	275.000 470.000
Source: Progress Reports from the "RP&M `97" Conference, Dearborn, April 1997			

Table 12: Prices of RP machines in the USA, April 1997

Price	Machine Model
$2,295	Roland CAMM-1 Vinyl Cutter
$4,495	Roland Modela MDX-20 Milling Machine.
$6,400	Denford Micromill 2000
$9,995	Universal Laser Systems desktop VersaLaser 200
$17,250	Universal Laser Systems M-300 Laser Platform
$24,900	Dimension 3D Printer (FDM)
$25,050	Universal Laser Systems X-660 (25 watt) Laser Platform
$31,800	Z Corporation ZPrinter 310 System
$39,900	3D Systems InVision 3D Printer
$39,999	HAAS Super Mini Mill
$49,900	3D Systems Thermojet Printer
$119,000	OMAX 2652 Jet Machining Centerup to $180,000)
$169,000	3D Systems Viper SLA System

Table 13: Prices of digital fabrication machines in April, 2004, (Seely, Jennifer C.K. and Sass, Larry. 2004).

Besides the high cost of the mentioned machines, most of these machines require annual maintenance, which can also be quite costly as well as the continually evolving technologies which are costly and time-consuming.

Another factor is that the “cost of outsourcing” of RP and CNC processes which provided by some companies for modeling and construction the parts of the required work. For instance; “The Palladio model’s dimensions are 0.896m x 1.475m x 2.371m and the prices ranged from $281 for a 3DP to $814 for an SLA print” (Seely, Jennifer C.K. and Sass, Larry. 2004). Also, altering the design process to accommodate 3D printing needs can cost companies even more time and money.

Another factor is that to have the final work produced by digital machines it must be learned some three-dimensional software which is the preparing of the final file format to be exported to the machine. Therefore; trying new technologies and latest software is taking much time to learn and to be incorporated in their design exploration as well.

CHAPTER SIX

FABRICATION IN DIGITAL FORM

At this chapter it is going to be investegated that how digital fabrication machines work and what are the major steps that the designer trying to set-up while manipulating his/her final concept to be physically fabricated. As the involvement of the study is to trac the production process of the form using digital technology equipments, the study traying to clarify the methods of using those machines as well as the fabrication process of how the machines work to built up the final form.

When employing digital fabrication methods in the model making process, the user has almost no control of the tool at the moment it is manipulating the material. All digital methods start by the user setting up a file in the computer and end by the user sending the file to the machine. The user has varying amounts of control over the manipulation of the material during set up, but once the file has been sent, the user can do little but watch. There are rare exceptions where some machines allow the user to slow down or speed up the process of manipulation, but never the manipulation itself .

The thesis categorizes the digital fabrication methods according to the term of use into two groups: computer numerical control (CNC) processes and rapid prototyping (RP) processes. The fundamental difference between these two is that the CNC processes all work through subtractive methods of manipulating material to create the final object, while all RP processes utilize additive methods of building up material layer-by-layer.

It should be known that all of these processes were originally developed for use in industrial design and manufacturing. Machines designed for use in industrial shops are typically difficult for an architect or student to use because there are too many factors that must be considered to efficiently operate on his or her own. However, many of these processes have been compacted into smaller, more user friendly machines that are more suitable for architecture offices and studio environments. This has made it easier for designers to use the machines in architectural model making.

6.1. Digital Fabrication Methods

6.1.1. Computer Numerical Control (CNC) Process

All of the fabrication methods categorized as CNC processes "create objects by removing material from a starting block, rod, or sheet through computer controlled movements" (Seely, Jennifer C.K. and Sass, Larry. 2004). The user starts the process by preparing a file in the computer, sets up the material in the machine, and then sends the file to the machine. The machine automatically mills or cuts the material according to the computerized directions it is given.

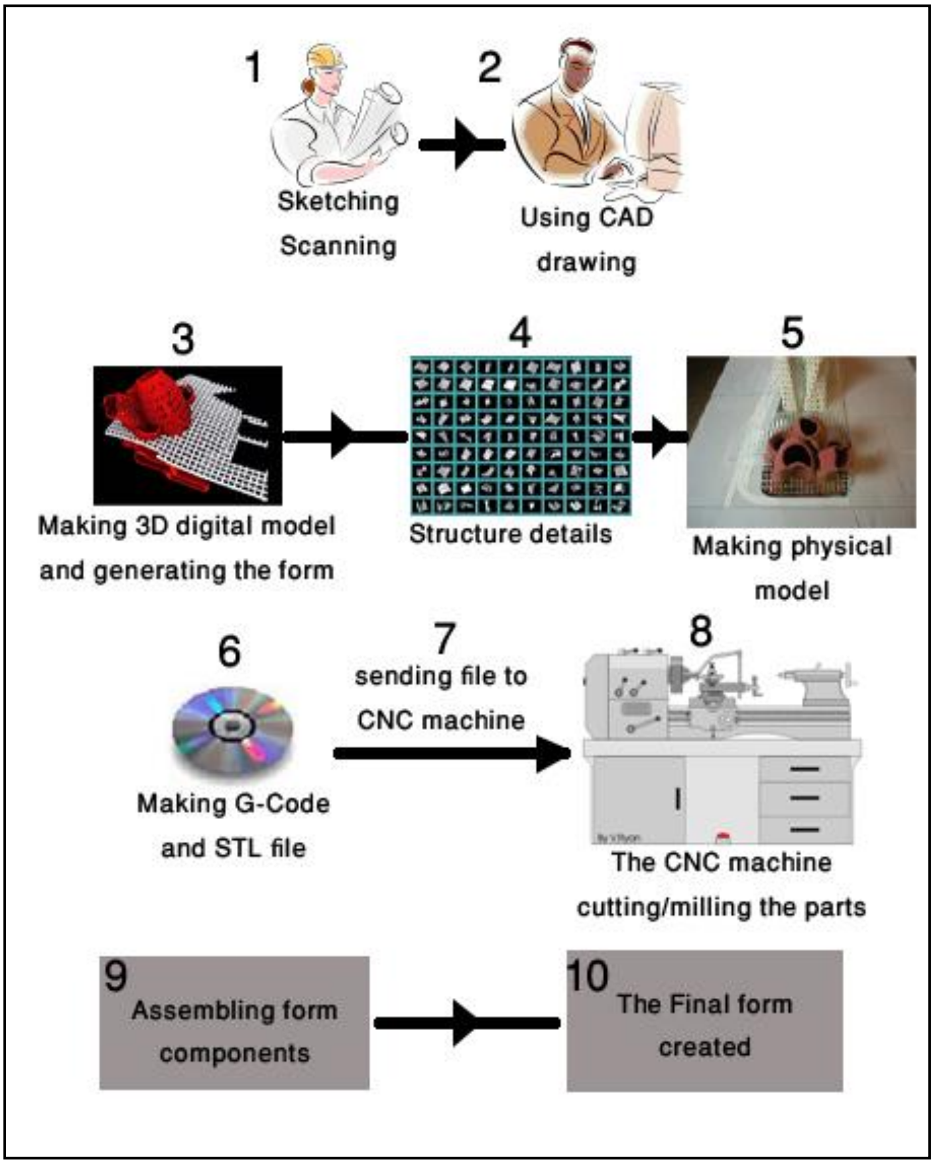


Figure 168: Computer Numerical Control (CNC) Process

6.1.2. Rapid Prototyping (RP) Process

All of the fabrication methods categorized as rapid prototyping (RP) “create objects by building up material layer-by-layer through computer controlled movements” (Seely, Jennifer C.K. and Sass, Larry. 2004). The way the process is started is generally the same as it is for CNC processes. The user starts by preparing a three-dimensional file in the computer, sets up the machine, and then sends the file to be printed. The machine automatically builds up the material according to the computerized directions it is given.

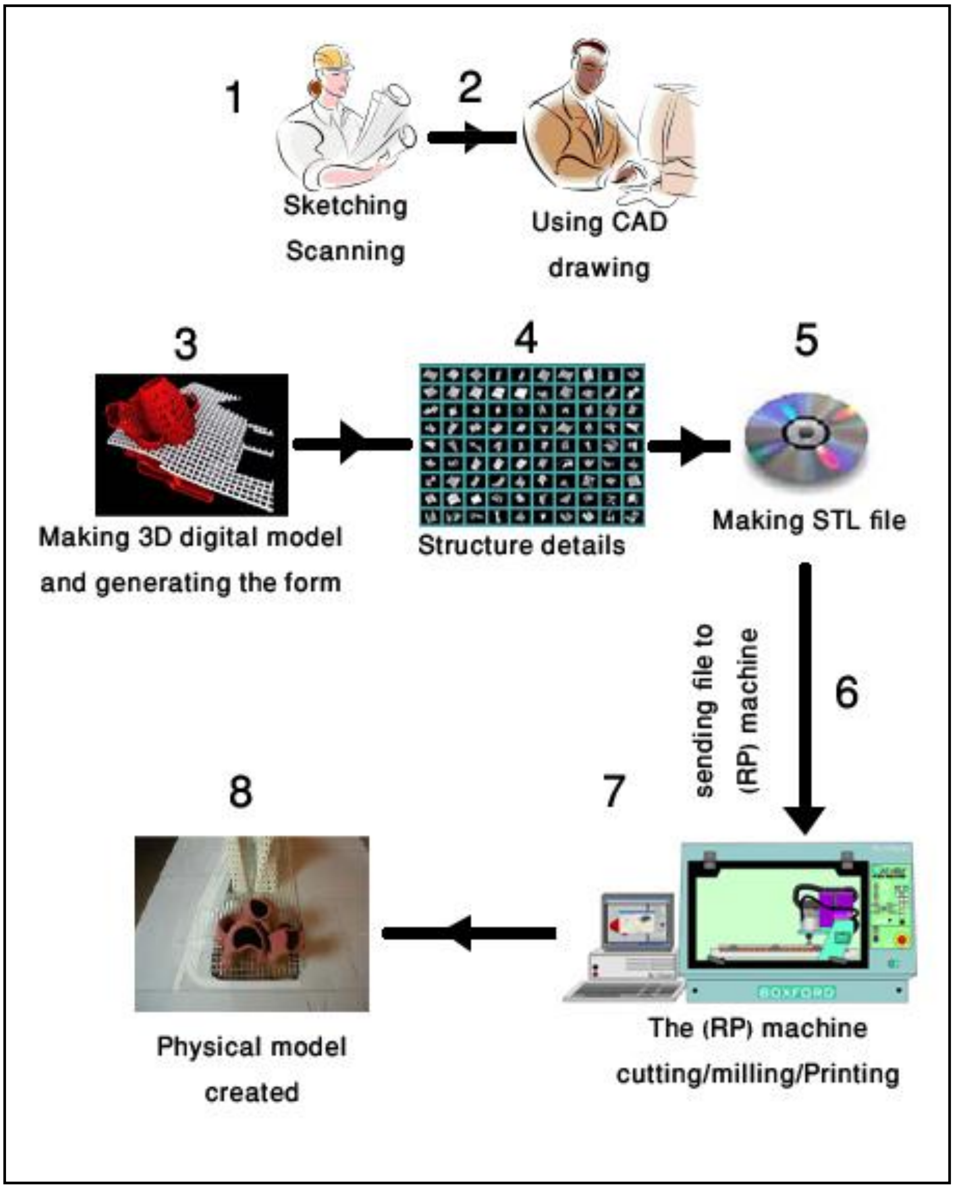


Figure 169: Rapid Prototyping (RP) Process.

6.1.3. File to Machine Process

The connection between the completed file that needs to be produced and the fabrication machines is another critical point that the thesis trying to explore. This step can be defined as the process that can translate the over all concept from being just a model or drawing into logical geometry which then will be translated to become a building or any active form.

As many architects used some soft wares that can be connected to the computer to get the model from the computer and join it to the machine process, which then will be divided into some parts. Those parts of the model will be cut precisely into certain shapes which will be collected or welded later to combine the final form. However; the most known fabrication process which known as “file to factory” or “design documentation” that being used among the recently works of the contemporary architects are using **Lamina, CATIA** or **feature-CAM** software during the fabrication stage. Because they are similar in use, one of those types has been discussed through this section to have better understanding of how the completed work can be transferred from the file format to the fabrication machine. More detailed information about using CATIA was discussed in ***www.plm.3ds.com/CATIA*** **or www.ibm.com.**

6.1.3.1. Using Lamina Software

Lamina software uses computer methods to build up the final formated file from CAD drawing into digital format that can be red by the fabrication machines. The 3D model is “approximated by a number of 2D parts” that are numerically cut and attached to produce the final structure. “Laser cutting, abrasive waterjet cutting and plasma cutting services are widely available and make creating parts inexpensive and fast”. This new software package enables the production of large-scale, free-form structures from planar materials like “plywood, plastic, and metal”. Useful for a wide range of architectural production, including interior finishes, lighting and product design, and custom signage, Lamina works by taking a 3D model file and “breaking up” the structure into machinable 2D parts that are fabricated using “laser cutting, waterjet cutting, or plasma cutting”, depending on the material used and the size of the desired end product. The software “automatically” accounts for material properties like “thickness and flexibility, and subsequently adjusts joining angles and joint types automatically" during the cutting process. The preferred 3D file formats that Lamina can accept are "OBJ and 3DS-formatted files", but it can also use "STL" files, which are common in digital production [19], [20].

6.1.3.2. Lamina Supported file formats

Lamina can read input files in these "formats" [21]:

- Stereolithography .STL format
- Wavefront .obj format
- Rhino3d .3dm format
- 3D Studio Max .3ds format.

6.1.3.3. The process of using Lamina software

- **Importing three-dimensional model;** the shape in (figure 170) was modeled using trimmed NURBS in Rhino3d. The Rhino3d model "bone.3dm" was saved as polygonal mesh "bone.obj". Lamina can read input files in "STL, Wavefront .obj or 3D Sudio Max .3ds formats". It can also read "polygon meshes in Rhino .3dm files" [22].

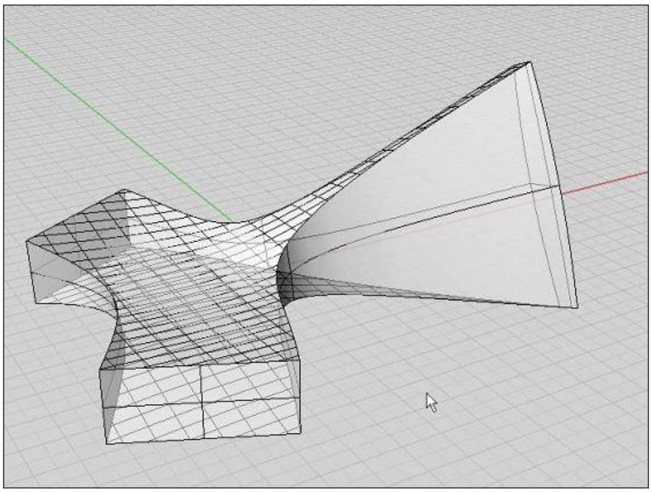


Figure 170: A NURBS model created with Rhino3d.

(Source: www.laminadesign.com)

- **Generating the parts;** lamina software automatically “subdivides the polygon mesh” into sections and each section is approximated by a 2D part. Lamina generates cutting paths in “DXF” format “bone.dxf” and a “PDF” file with assembly instructions [23] (Figures 171, 172).

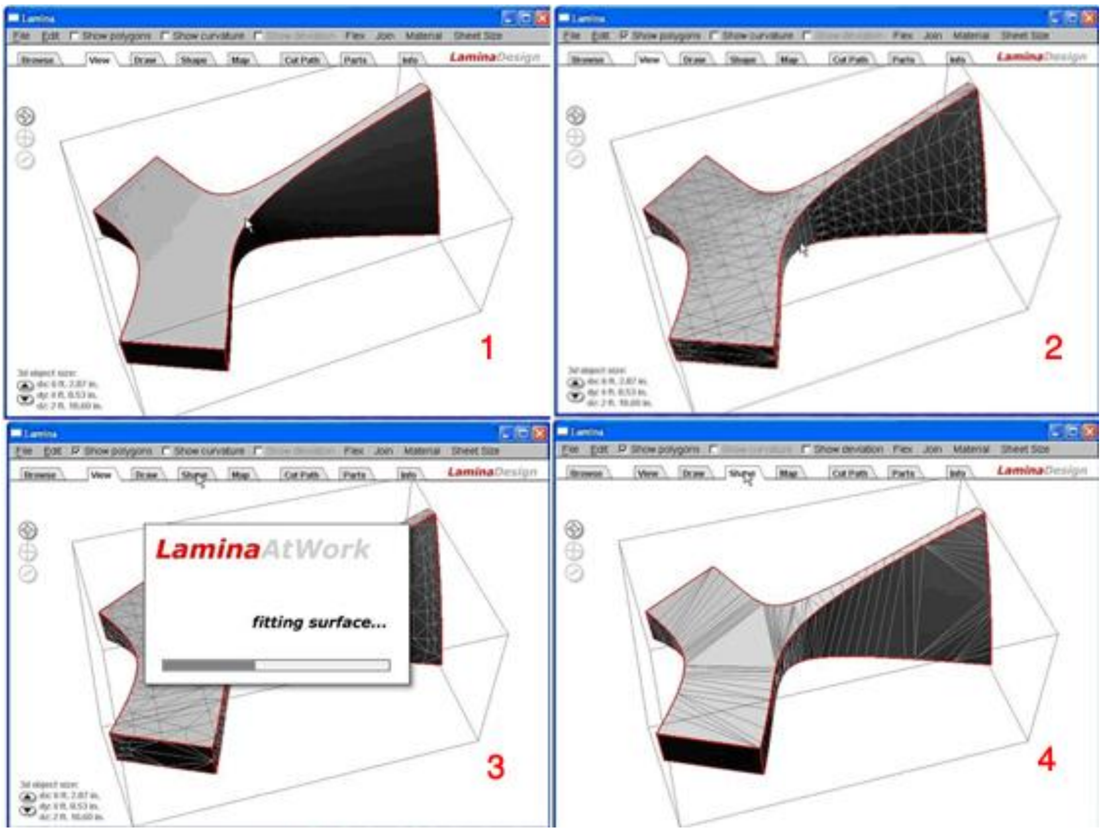


Figure 171: Generating the model parts by Lamina software.

(Source: www.laminadesign.com)

Figure 171 descriptions:

(1) Shaded input model

(2) Triangles of the input model

(3) Fitting input model with planar material

(4) The model approximated by planar parts.

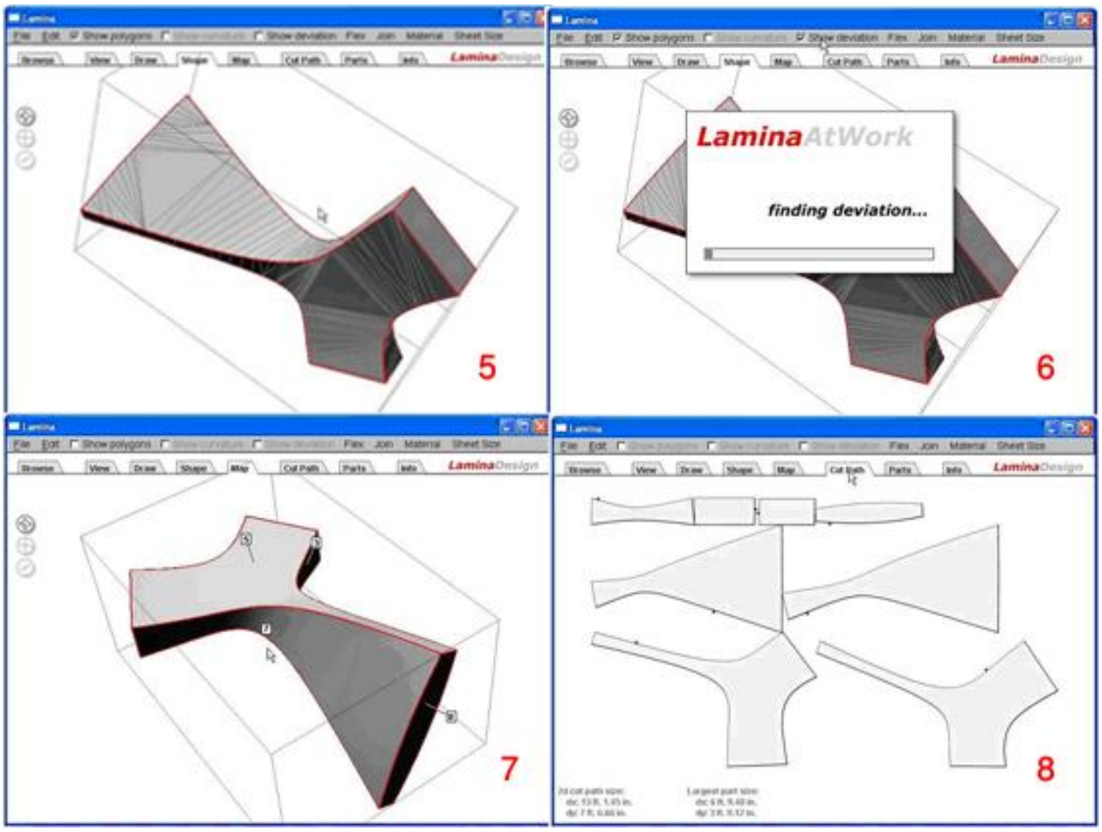


Figure 172: Calculating the deviation and locating the parts.

(Source: www.laminadesign.com)

Figure 172 descriptions:

(172-5) Bend lines are displayed

(172-6) Calculating the deviation from the input model

(172-7) As you rotate the 3-D model the location of parts and each visible section is labeled with its part number.

(172-8) The complete set of parts.

Also it can be seen the complete set of flat 2-D parts needed to produce the required design. There is one 2-D part for each section of the original model each region outlined by colored cut lines in the 3-D views. Lamina provides the dimensions of each part as laid out in the window to give a general sense of the size of all parts and also the dimensions of the largest part as shown in (figure 173).

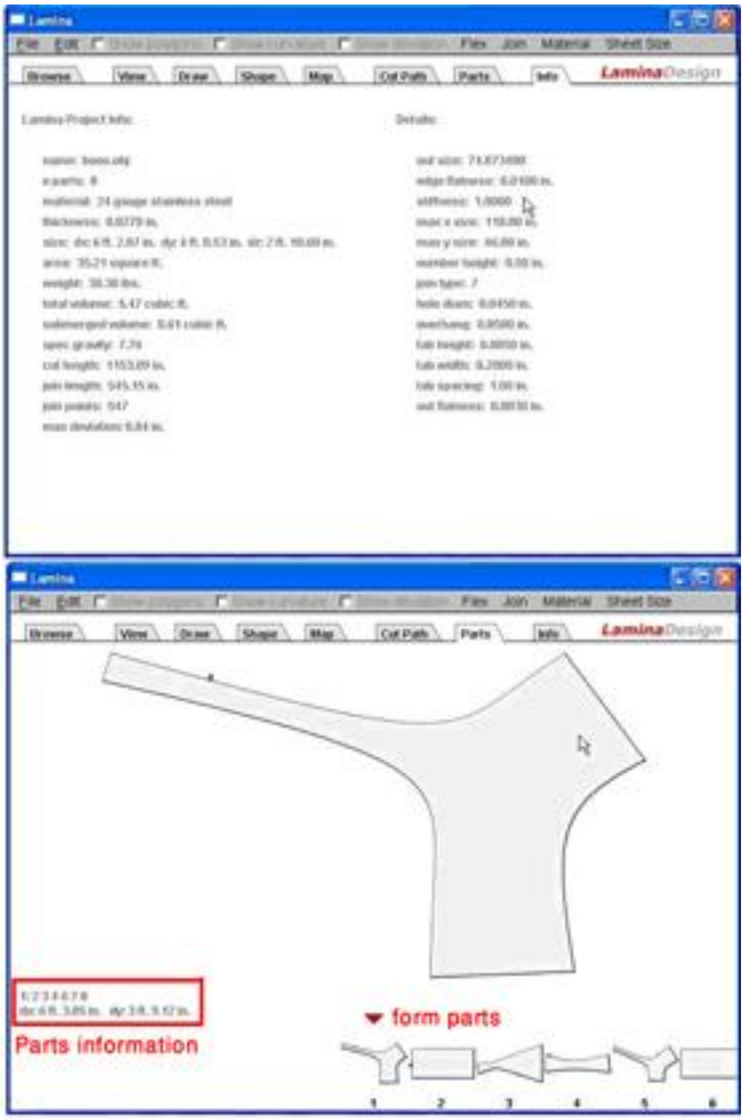


Figure 173: Detailed information on each part and bringing the General information about the project.

(Source: www.laminadesign.com)

- **Building the form;** the “DXF file” was used to cut stainless steel parts on an abrasive waterjet cutter. “A group of welders built the sculpture in 3 hours” [24]. As shown in (figures 174, 175).

Figure 174: The waterjet cutter was used for cutting stainless steel parts, then the staff starting welding the parts

(Source: www.laminadesign.com)

Figure 175: The form is completed and ready for the final step.

(Source: www.laminadesign.com)

- The finished form; After grinding and sanding the welds, this is the final result. (Figure 176)

Figure 176: The finished form.

(Source: www.laminadesign.com)

This was a sample of how the free-form or any complicated form could be produced using digital fabrication process, the same process can be done for making large scale form by defining the dimensions of the required form then the system will cut the pieces which can be welded and combine together as mentioned above to become a completed form.

6.2. Fabricating Building Digitally

Digital technology and industrial design have brought several ways as mentioned before to help the designers, engineers and architects to build their ideas. At the same time they may share their thoughts to improve the machines or the process of production to get the required results. As the study clarified the types of digital fabrication machines and their process, the thesis trying to resume the process of the discussed machines which have been used extensively on a number of recently completed projects worldwide.

Figure 177: Zollhof Towers, Germany 2000.

(Source: http://en.structurae.de/photos/index.cfm?JS=58068)

In CNC milling "subtractive fabrication", that has recently been applied in new ways in the building industry to produce the formwork for the off-site and on site casting of concrete elements with complex geometry. In one of the office buildings (*Zollhof Towers*) in Düsseldorf, Germany (2000) (figure 177), designed by Frank Gehry, the undulating forms of external wall panels, made of "reinforced concrete, were produced using blocks of lightweight polystyrene" (Styrofoam) that were shaped in "CATIA and were CNC milled to produce 355 different curved molds" that became the forms for the casting of the concrete. "CNC milling can be also used to produce doubly curved molds for the shaping of glass panels with complex geometry", as in Gehry's *Condé Nast Cafeteria* project in New York (2000) or Bernard Franken's "*Bubble*" BMW pavilion (1999) (Branko Kolarevic, 2003) (figures 178. 179).

Figure 178: Gehry's *Condé Nast Cafeteria* project in New York (2000), (El Croquis 103 magazine)

Figure 179: Bernard Franken's "*Bubble*" BMW pavilion (1999).

(Sources: http://lapa.epfl.ch/downloads/programming_as_design_method.ppt. & http://www.franken-architekten.de/)

Whereas; in the “additive fabrication” process (Rapid Prototyping) due to the limited size of the objects that could be produced, costly equipment and lengthy production times, the additive fabrication processes have a rather limited application in building design and production. In design, as discussed by Branko Kolarevic they are used mainly for “the fabrication of study models”. In construction, they are used to produce “components in series, such as steel elements in light truss structures, by creating patterns that are then used in investment casting” (Branko Kolarevic, 2003).

In “formative fabrication, mechanical forces, restricting forms, heat or steam” are applied to a material so as to form it into the desired shape through reshaping or deformation, which can be “axially or surface constrained” (Branko Kolarevic, 2003). For example, plane curves can be fabricated by the CNC bending of rods, tubes or strips of elastic material, as was done in several pavilions designed by Bernhard Franken for BMW.

After the components are digitally fabricated, their assembly on site can be augmented with digital technologies. Digital three-dimensional models can be used to precisely determine the location of each component, move each component to its location and, finally, fix each component in its proper place. “Components can be bar coded and the bar codes can be then swiped on site to reveal the location of each component by displaying them within the 3D digital model of the building. Electronic surveying and laser positioning equipment, driven by the 3D digital data such as GPS, can be then used to precisely determine the position of each component”. (Branko Kolarevic, 2003)

The digital design information can be used directly in fabrication and construction to drive the computer-controlled machinery, making the time-consuming production of drawings unnecessary. This newfound ability to generate construction information directly from design information is what defines the most profound aspect of contemporary architecture. The close relationship that once existed between architecture and construction could potentially reemerge as an unintended but fortunate outcome of the new digital processes of production.

By using digital building information models, the processes of describing and constructing a design can be now more direct and more complex because the information can be extracted, exchanged and utilized with far greater facility and speed; in short, with the use of digital technologies, the design information is the construction information.

By integrating design, analysis, manufacture, and the assembly of buildings around digital technologies, architects, engineers and builders have an opportunity to fundamentally redefine the relationships between conception and production. “The currently separate professional realms of architecture, engineering, and construction can be integrated into a relatively seamless digital collaborative enterprise and digital praxis” (Branko Kolarevic, 2003).

CHAPTER SEVEN

CASES OF FORM PRODUCTION PROCESS IN DIGITAL ARCHITECTURE

The study required to analyzing the following architect's projects which are considered as the recently and the most notable projects that have been done in the 21st century. The collected works would approve the objectives of the thesis. The process of analysis will be through the main thought of every architect, starting from designing the concept, modelling the form (Generating the form), ending with the production of final from. The main points that will be discussed through the analysis are the theory, method or technique used during the design process as well as the design generation in which the form developed and both visually and physically perceived. Then defining the structure elements "form elements" ending with the final form by which fabrication process used to build the form. By investigating every process of different architect which consists of using digital tools that would finalize the objectives of the study, the thesis will conclude the production of digital form into one diagram that describes every step of the production process which may guide the designers to understanding the major steps of producing digital form by the aid of digital technology.

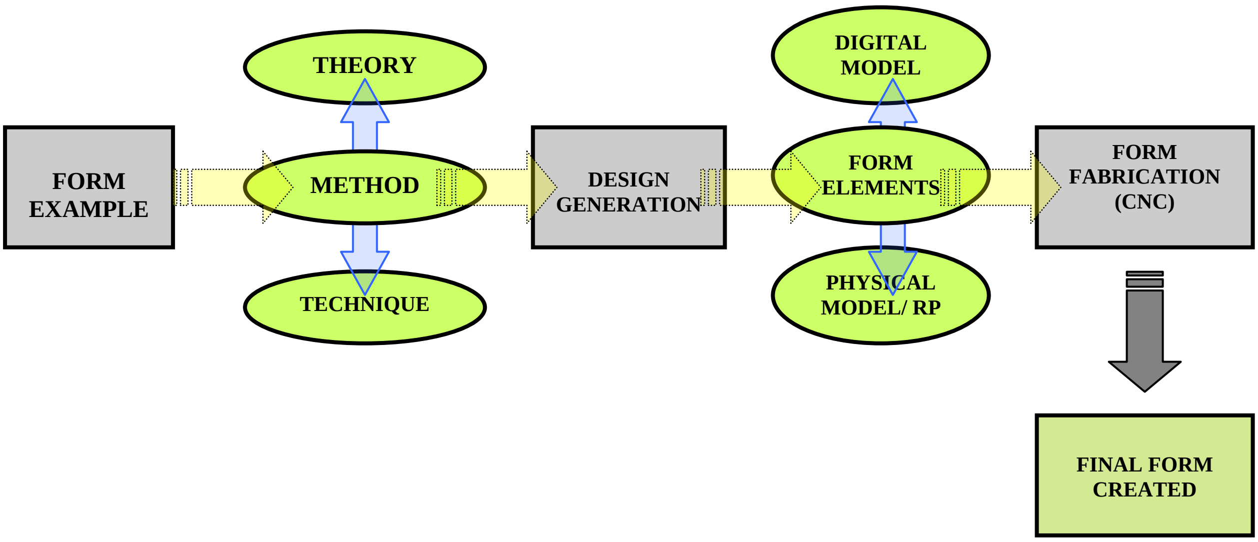
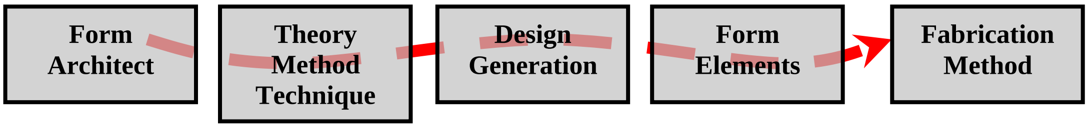


Figure 180: Analysis format.

ANALYSIS PROCESS



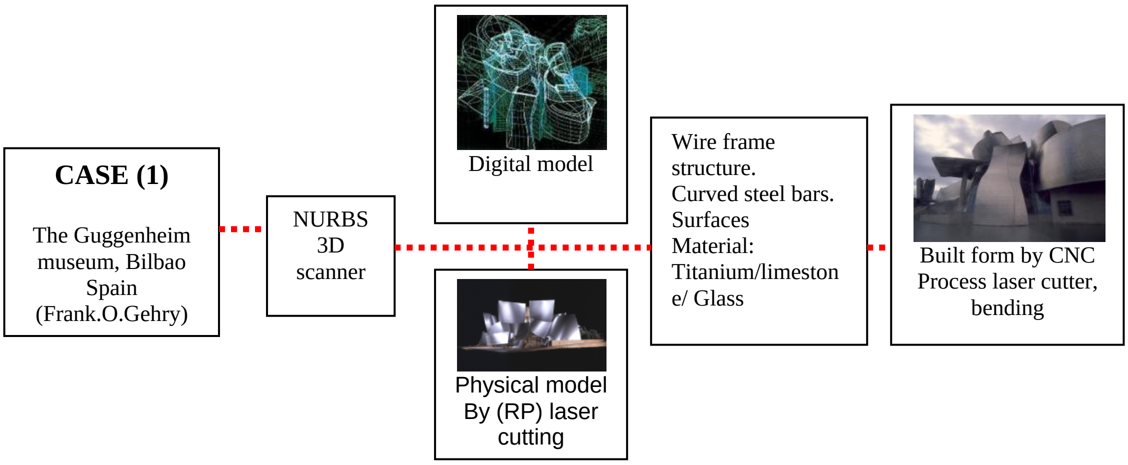


Figure 181: Case (1) Process

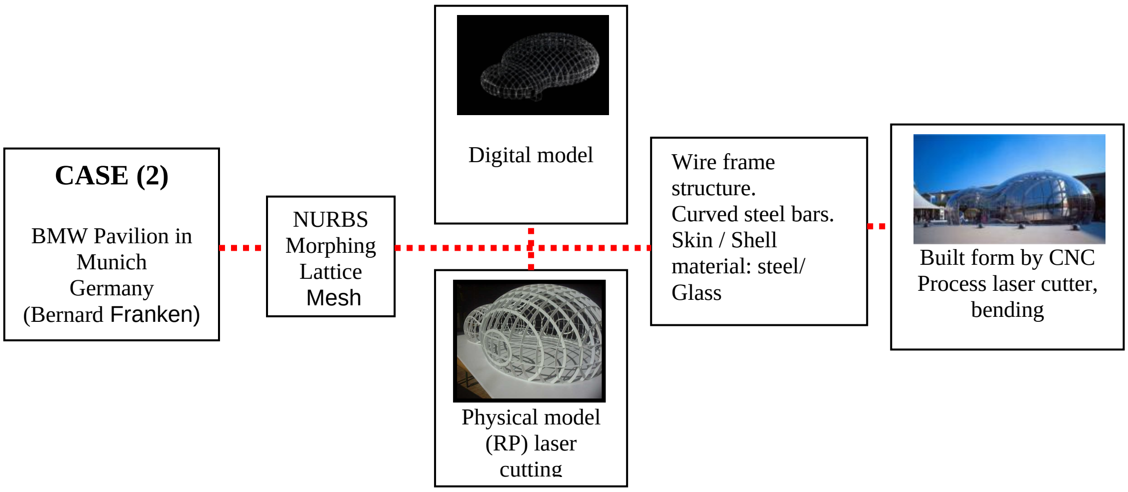


Figure 182: Case (2) Process

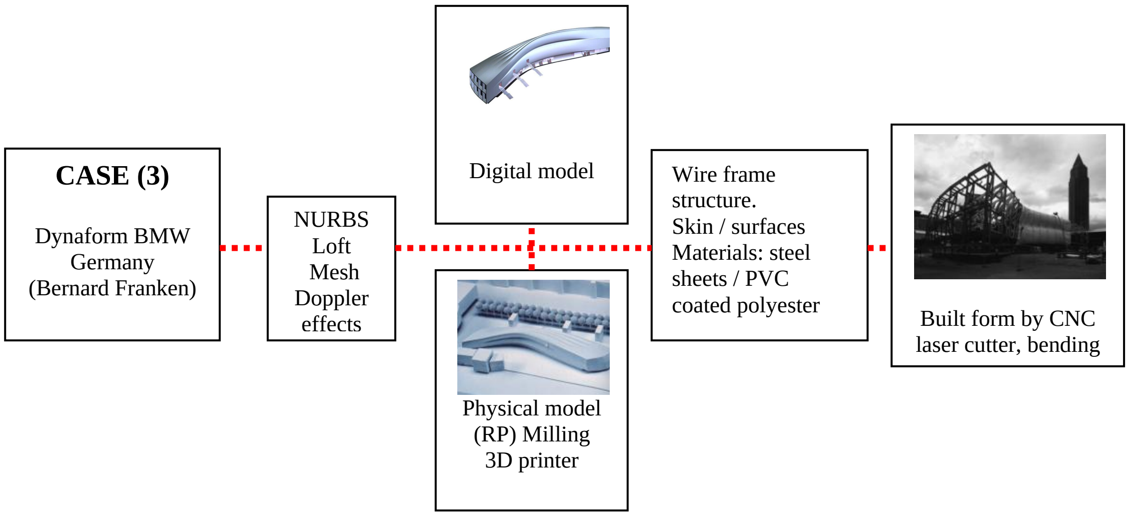


Figure 183: Case (3) Process

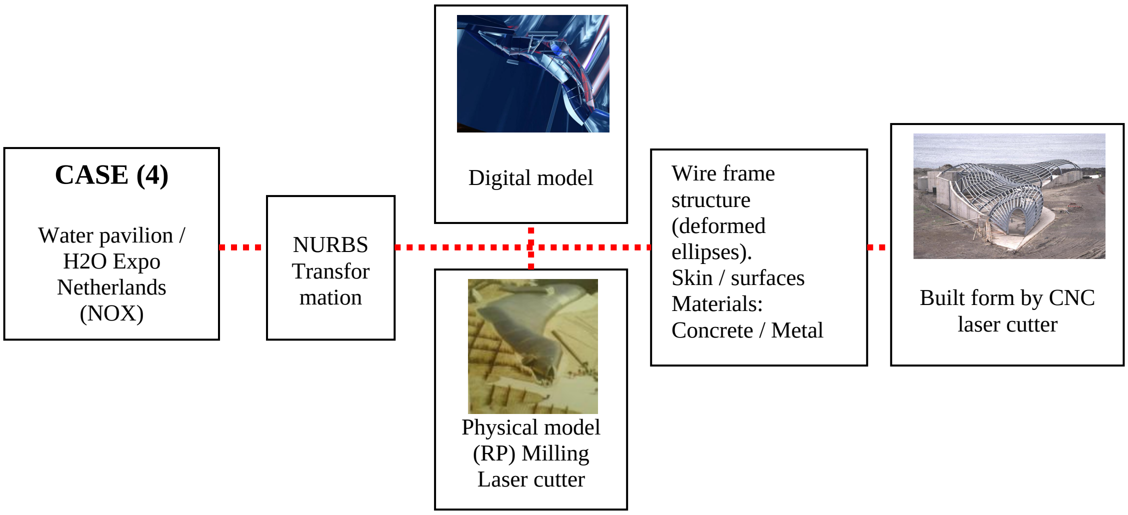


Figure 184: Case (4) Process

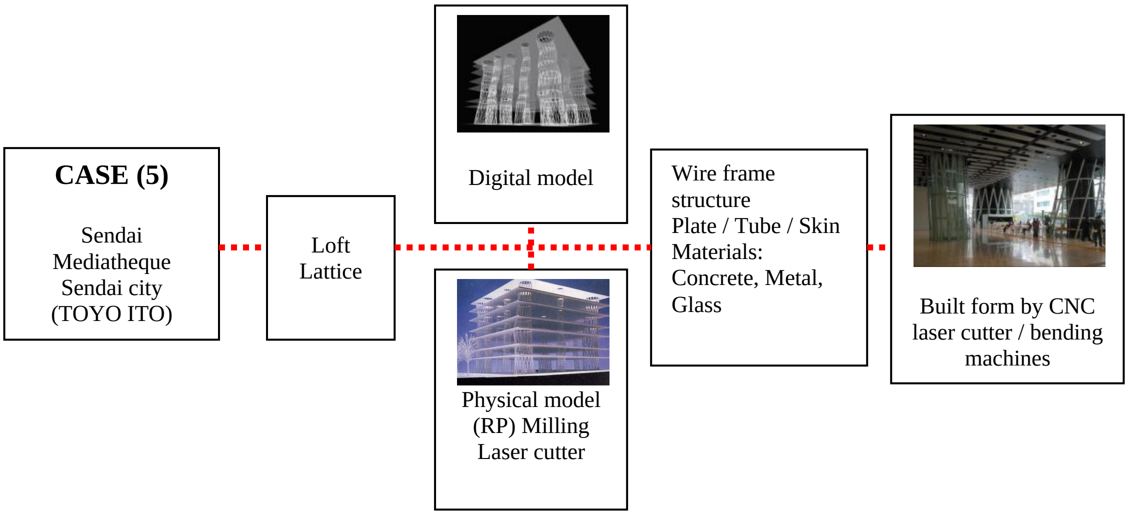


Figure 185: Case (5) Process.

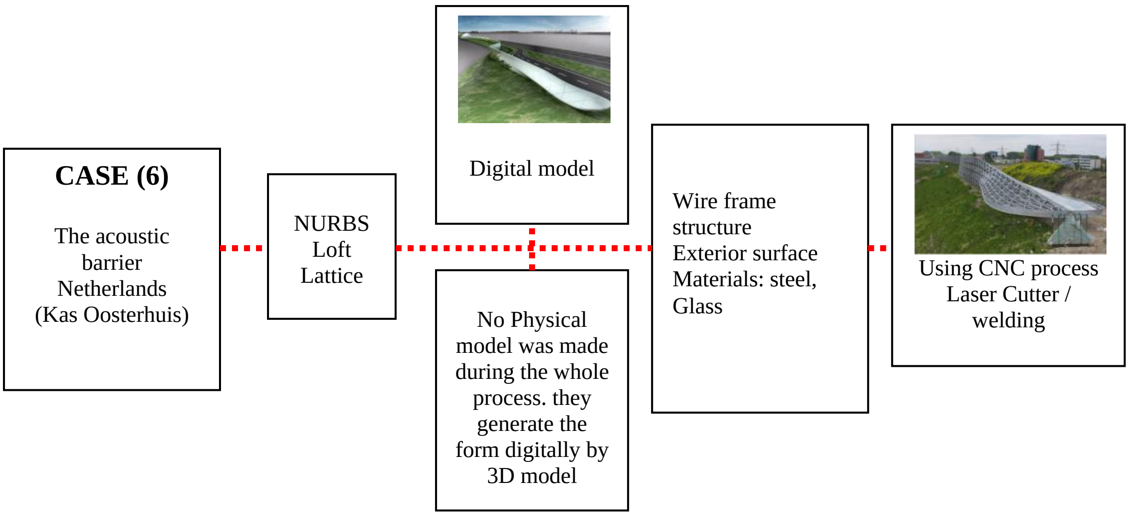


Figure 186: Case (6) Process.

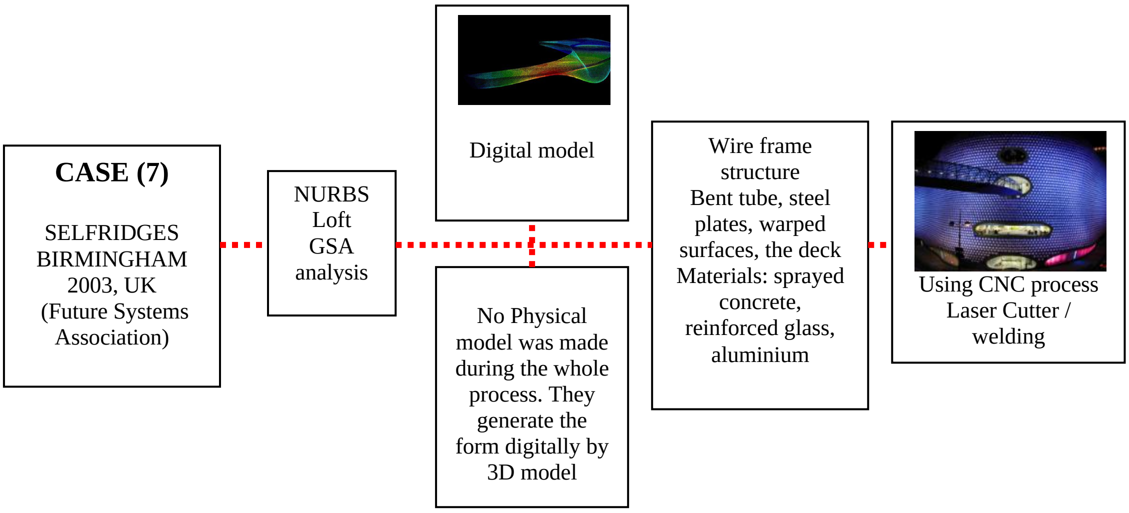


Figure 187: Case (7) Process

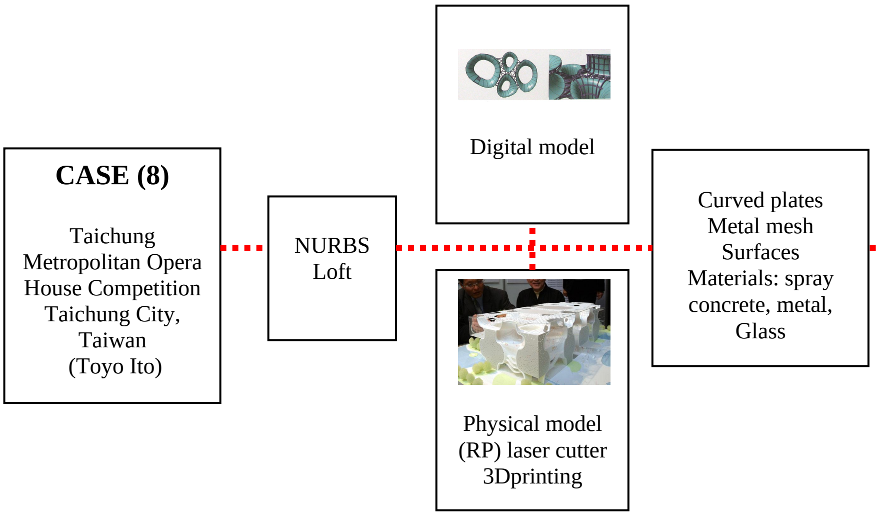


Figure 188: Case (8) Process.

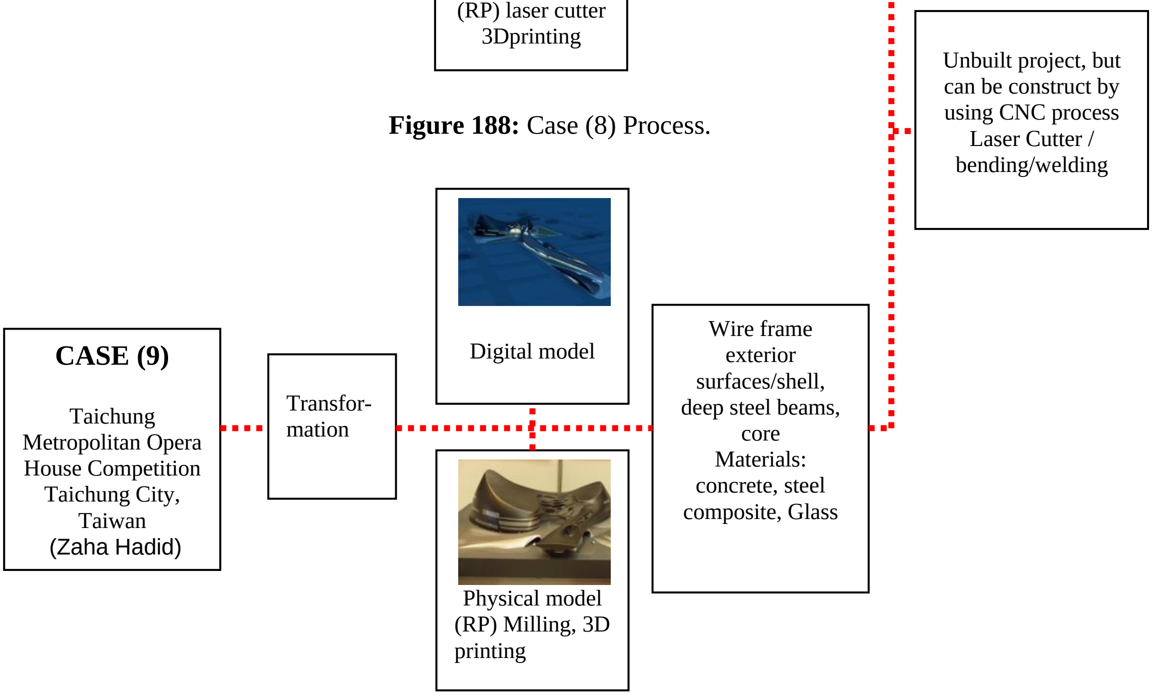


Figure 189: Case (9) Process.

7.1. Case (1):

Guggenheim Bilbao Museum, Spain, By Frank.O.Gehry

Due to his use of computer, Frank.O.Gehry designed the Guggenheim Bilbao (figure 190) to be the "first modern building to represent technology as it subsumes the idea of industry. This transfiguration of technology is fundamental to the thesis that Gehry has presented a paradigmatically shift in architecture, resulting from what is now commonly being referred to as digital technology" (Irene Nero, 2001).In addition, the building has been formed through technological means. Through this section the main though and major steps of Ghery's design process will be discussed.

Figure 190: Frank Gehry, Guggenheim Bilbao museum, Spain.
(Source: http://www.Wikipedia.com)

7.1.1. Design Concept

By using a computer program, Gahry translated his sketchy, hand-drawn designs directly into workable computerized drawings. He showed that the ideas could coexist in a building. Furthermore, the architect was able to transform the resultant graphics into pre-fabricated sections that were assembled on site. Bilbao museum nestled into its environment, reflecting all levels and sources of light; creating a continually changing façade (figure 191, 192). In the context of form shape, no straight lines had been used through the plan, facades and even at the interior spaces which is made the building difficult to be constructed by the conventional process.

Figure 191: Frank O.Gehry, Guggenheim museum, 1997, river façade (Irene Nero, 2001).

Figure 192: Guggenheim museum site.

(Source: ©2006 Google-imagery @2006 DigitalGlobe, Map data @2006 TeleAtlas)

7.1.2. Design process:

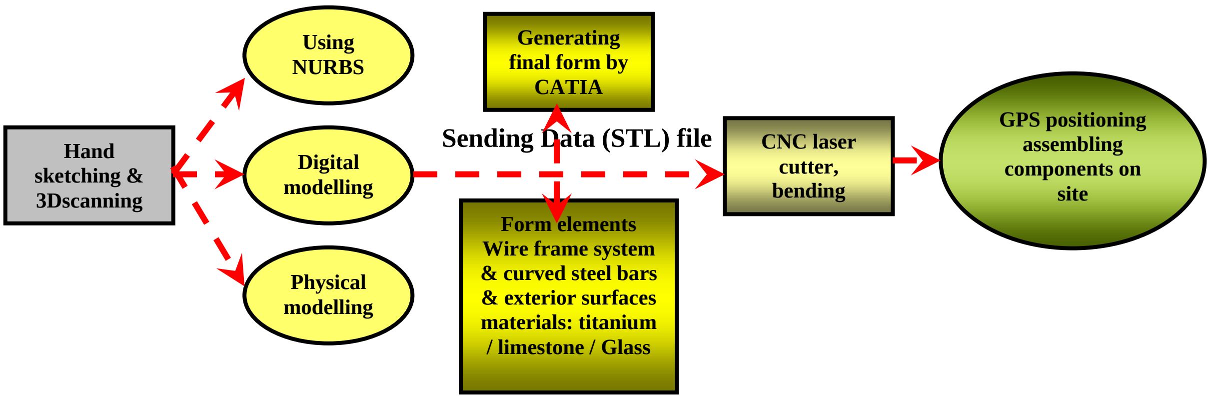


Figure 193: Frank Gehry design Process.

Basically, as discussed by Coosje van Bruggen that Gehry begins every project with sketches using “pen and paper”, and continues to use an enormous amount of sketching and “3D image scanning” throughout the design process. When he has a relatively sound idea in mind, Gehry makes a number of models for visualization purposes by using “French aerospace computer program known as CATIA” (computer aided three-dimensional interactive applications) (Coosje van Bruggen, 1997).

By using the software program to help realizing his design Gehry attended to use “NURBS method” to manipulate the complicated curves. AutoCAD systems which are mainly automatic assistance to planar design do not possess the precision and range that the aerospace program provides. Therefore, with “CATIA”, the shell is formed before the skeletal system of the main form of the building. In terms of design, Gehry’s use and modification of CATIA is “unprecedented”. “CATIA was designed to accommodate subtle and grand curves, and surface variations found in airplanes” (The 54th Conference, 2001) & (Irene Nero, 2001). Gehry's staff would carefully measure his hand-crafted models, perform lengthy calculations, and prepare multiple sections and plan cuts trying to describe the design. Unfortunately, such drawings are time- consuming, costly and tended to make the shape seem more complex than it actually was. “Contractors, uncertain about how the unusual forms could actually be built, would be misjudged in their cost estimates” [25].

Thus, that’s why Gehry had been looking for the best solution not only for constructing one or two project but also for the future works, which he found it at CATIA software that could “translates the very complex 3D models into physical model” even at the large scale. The architect himself admits to being “surprised” when he saw the construction of his concept’s curves, he was not certain they could be realized (Irene Nero, 2001).

> *“With this technology you know exactly where you are going before you start construction, so you minimize the surprise from the owner’s standpoint” Frank Gehry, 2003*

"This technology provides a way for me to get closer to the craft. In the past, there were many layers between my rough sketch and the final building, and the feeling of the design could get lost before it reached the craftsman. It feels like I've been speaking a foreign language, and now, all of a sudden, the craftsman understands me. In this case, the computer is not dehumanizing; it's an interpreter." ...Frank Gehry (Irene Nero, 2001).

It’s simply said, Gehry would not have been able to produce the form of his building; because such a technique that has been used by the architect had not been done during that period. But he certainly done his concept; not only that also he considered being as the “first architect who integrate such a technology with architecture” (Irene Nero, 2001). The architect’s new design methodologies, new technology, and new materials have all allowed for a new architectural vocabulary and design process.

Critic Paul Goldberger noted that “changes in architecture have already moved ahead of Gehry; while Gehry designs in his head and implements with the computer, a new generation have adopted the computer itself as the generator of design. Still, Gehry's work could not be implemented without the use of computers.” [26].

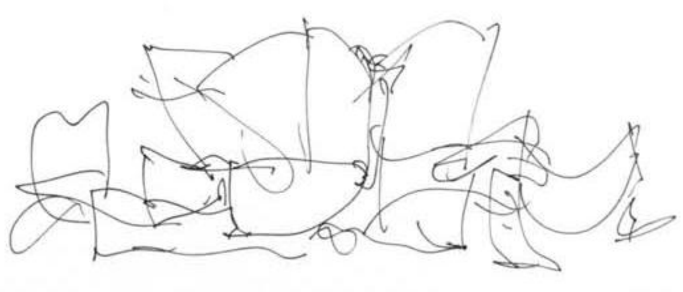


Figure 194: Gehry’s hand sketch, (EL Croquis 103).

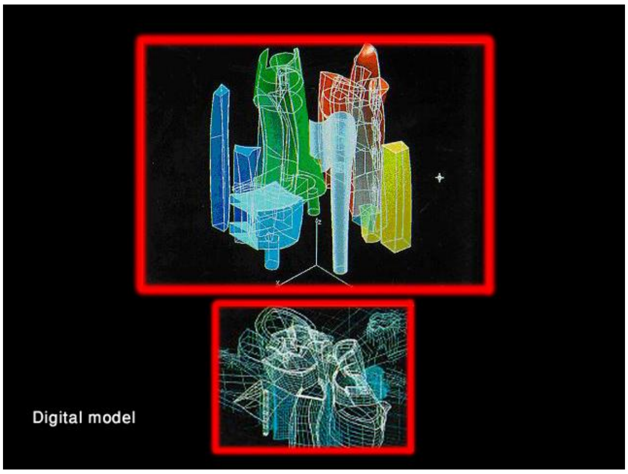


Figure 195: The technique of using digital modeling “CATIA” during the design process.

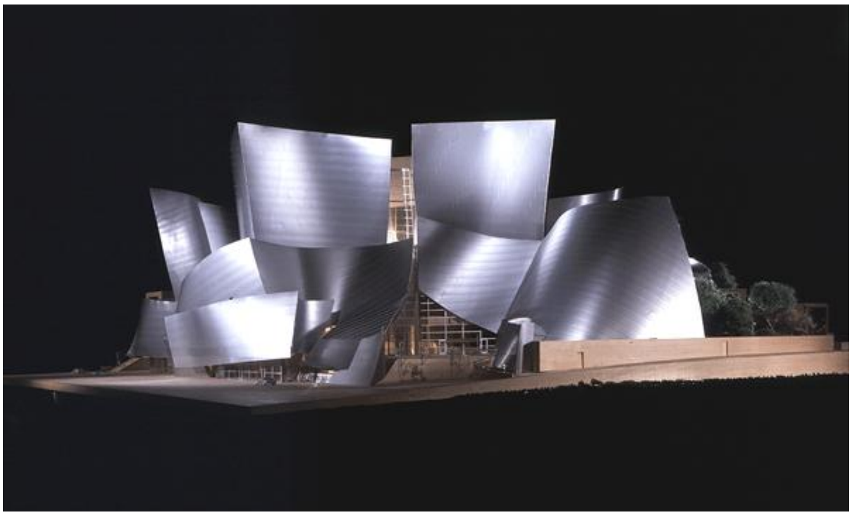


Figure 196: The physical model of the Guggenheim form.

(Source: http://lapa.epfl.ch/downloads/programming_as_design_method.ppt.)

Figure 197: Modeling of the Guggenheim Museum in Bilbao. From left: Physical, during digitization & digital, (Marc Aurel Schnabel, Thomas Kvan, 2004)

7.1.3. Structure details:

The structure can be divided into four main elements:

1- The wireframe system: The repeating 3'x3' steel truss system. This system of relatively small square trusses helps to standardize an otherwise highly complex form (figure 198). The trusses are hooked together with a universal joint and hug the curving form as closely as possible. This is the main structure of the building which supports much of the exterior form's weight.

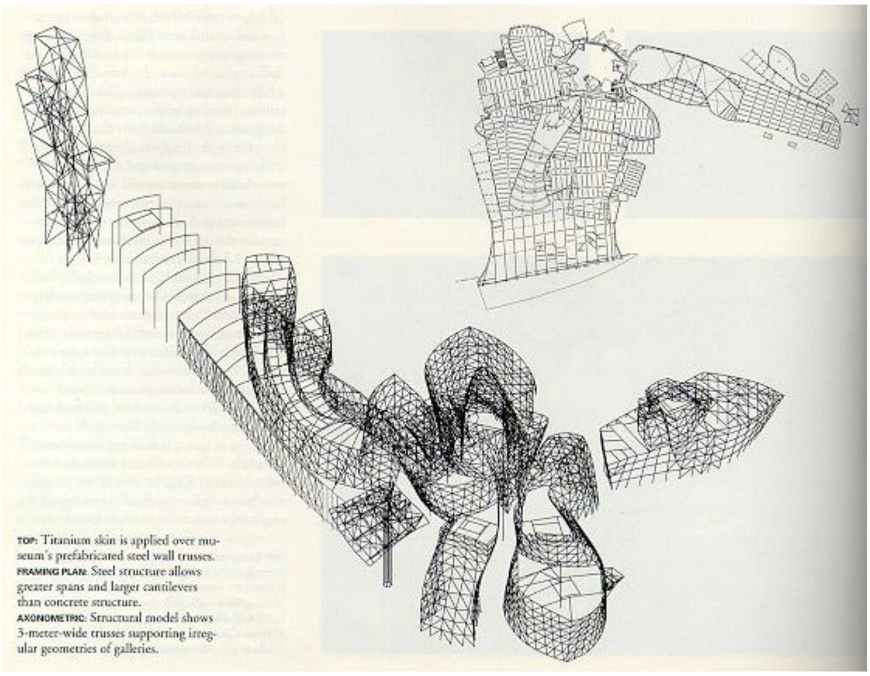


Figure 198: The wireframe and truss system

(Source: http://caad.arch.ethz.ch/teaching/nds/ws98/script/object/st-object4.html)

2- The curves / steel bars: The relatively thin bars of steel which were placed horizontally first, and then vertically. These bars are welded to the main structure and serve to produce the curving form more exactly, where the trusses can only make a close approximation being that each truss itself is flat on the outer surface.

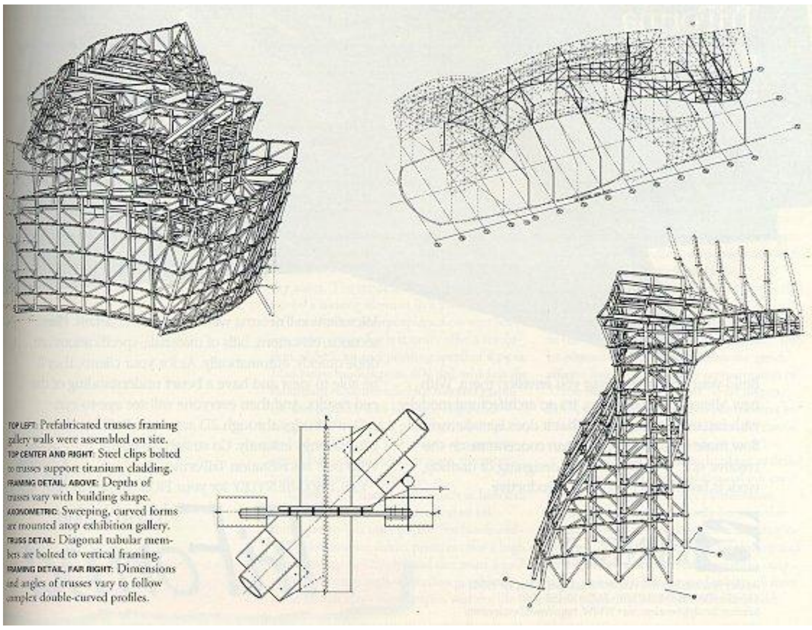


Figure 199: The curved steel bars of the structure.

(Source: http://caad.arch.ethz.ch/teaching/nds/ws98/script/object/st-object4.html)

Figure 200: The real structure of the main form indicating the curved steel bars and the wireframe system.

(Source: http://www.culturevulture.net/ArtandArch/Bilbao.htm)

3- The surfaces and the choice of materials: After the curving steel bars which are the last basic layer of structural components, the exterior itself, or the considered surfaces of the "titanium" which offered the flexibility to manipulate the complicated shapes of the exterior surfaces. The scales of titanium are incredibly thin. However, one ironic aspect of this thinness is that the titanium would look quite heavy on the exterior if Gehry and his associates had not come to this realization. The titanium scales are instead not placed totally flat, but slightly “fluffed”, so to speak. As though the space between structure and titanium scales was literally a “pillow”. The surface becomes not a heavy looking aspect of the building, but a “rippling effect” is formed and it gives the exterior a light look in contradiction to the material used [27].

The types of materials used to cover the outer surfaces of the main form are consisting of three main types: The titanium / Limestone / Glass. (Figures 201, 202).

Figure 201: The types of used materials (titanium / limestone / and glass), Frank O. Gehry, 1997, (MANDOUR .A. MOHAMED, 2004).

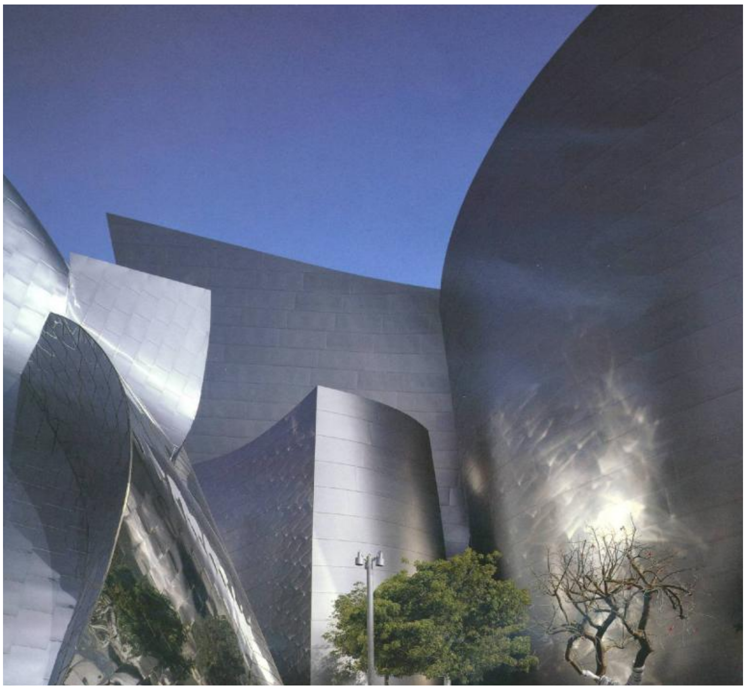


Figure 202: Titanium materials, (EL Croquis 103).

7.1.4. Construction process

Gehry's process of construction was by using the "3D CATIA surface model" which acted as the "master" model for dimensional control. The AutoCAD models were derived from CATIA geometry that was translated to AutoCAD using "IGES" through an in-house derived process. A complex "integration of CATIA and AutoCAD" had to be implemented in order to facilitate the design process and to satisfy the need for the quality of the construction documents [28]. Once each of the distinct pieces of the building were completed in CATIA, the CATIA model containing face and surface elements was sent out to a machine shop. A scale model was CNC milled directly from the CATIA data using a foam material. Each piece was then positioned to create a complete computer verification model to confirm the design to the project team (figure 203).

Figure 203: physical foam model of Guggenheim museum.
(Source: http://lapa.epfl.ch/downloads/programming_as_design_method.ppt.)

After the form components have been managed and coded in CATIA software they sent to CNC machines where they will be cutting and milling precisely (figure 204)

Figure 204: Plasma-arc CNC cutting machines for cutting the pieces,(Marc Aurel Schnabel, 2003)

Figure 205: Collecting the pieces at the site.
(Source: http://www.culturevulture.net/ArtandArch/Bilbao.htm

Figure 206: The building during the construction stage.

(Source: http://stellar.mit.edu/S/course/4/fa03/4.212/)

The last step was using new digital accessories such as electronic surveying, GPS positioning, construction part databases, and laser positioning, which are increasingly being used on construction sites to precisely determine the location of building components in 3D space. On the site, the workers constructing the steel frames verified that the correct pieces were being mounted by scanning the bar codes – relating the coordinates of each piece in reality to the CATIA 3D model. Laser surveying equipment linked to CATIA enabled each piece to be precisely placed in its position as defined by the computer model. This and similar processes are common to the shipbuilding and aerospace industry, but relatively new to architectural building.

Figure 207: The final built form of Guggenheim museum.

(Source: http://www.rockwool.dk/sw58000.asp)

7.2. Case (2):

BMW pavilion, Germany, By Bernard Franken

As mentioned in chapter three, the isomorphic concept can be seen in the work of Bernard Franken the BMW pavilion in Munich (figure 208). “Blobs or Metaballs”, as isomorphic polysurfaces are sometimes called, are amorphous objects constructed as “composite assemblages of mutually inflecting parametric objects with internal forces of mass and attraction. The geometry is constructed by computing a surface at which the composite field has the same intensity hence the name “isomorphic polysurfaces”. The surface boundary of the whole (the isomorphic polysurface) shifts or moves as “fields of influence vary in their location and intensity” (Kolarevic Branko, 2000).

Figure 208: The BMW pavilion in Munich, Bernard Franken.
(Source: http://www.franken-architekten.de/)

7.2.1. Design Concept

The concept of Meta-form “the Blob” can be described as asserted by Bernard franken as following:

> “*Bubble: to convey the feeling of water drop in a building, its form must express the delicate balance between the interior pressure and the surface tension of the water drop*” Bernard Franken. [29].

Figure 209: The concept of water drops.

(Source; http://www.franken-architekten.de/)

7.2.2. Design process

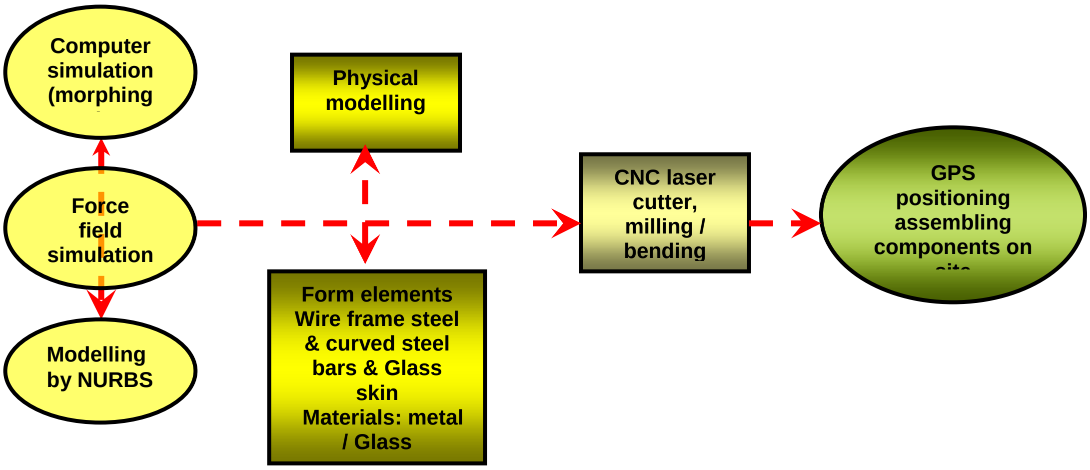


Figure 210: Bernard Franken Design Process of BMW pavilion.

The architect started to generate his primary concept through the concept of water – drop. He used the computer technique to simulate the two drops as can be seen in the Figures (211).

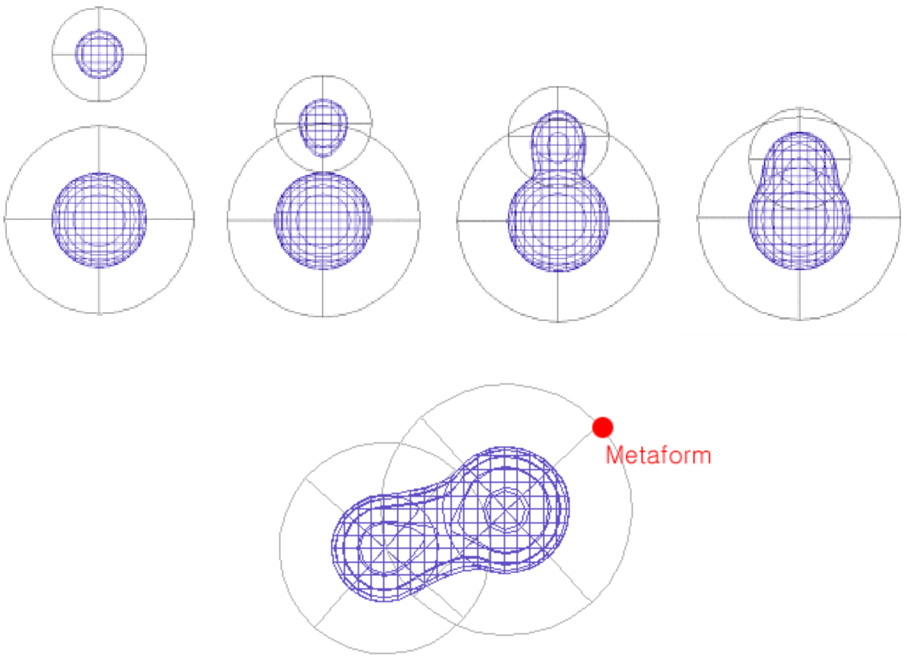


Figure 211: The top view of the simulated two spheres to generate the dynamic form.
(Source: http://www.franken-architekten.de/)

To Generate the Bubble; Bernard Franken implemented a computer program which "simulated water drops" to generate this dynamic form (figure 212) [30].

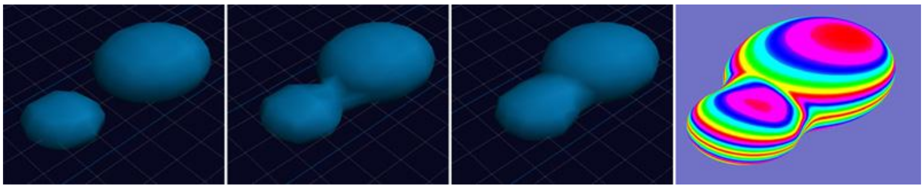


Figure 212: The simulation of water drops.
(Source : http://www.franken-architekten.de/)

The basic geometrical design created from the "force field simulations" were smoothed out and structurally calculated in special programs. "Load-bearing aluminum beams and 305 individual Plexi-glass panes" were created from the data (figure 213) [31].

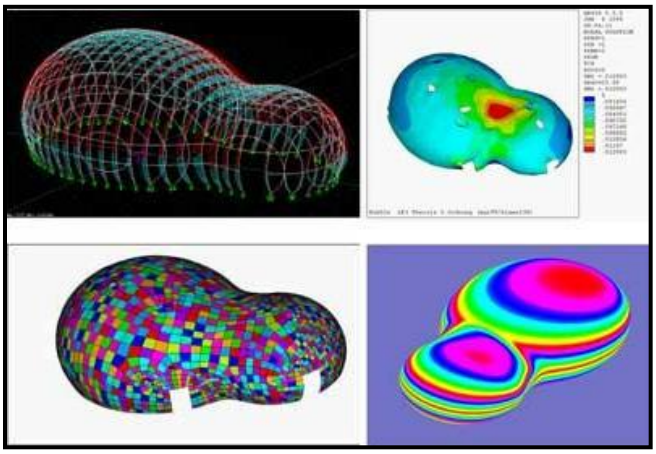


Figure 213: The process of force field simulations.

(Source: http://www.franken-architekten.de/)

For making the final form and defining the main structure; he seems to use the technique of NURBS for the final cover to physically produce the experimental model. The (figure 214) bellow illustrate the modeling technique using “NURBS” by using CV curves for creating the main form which then leads to define the individual elements of created form that can be defined as wireframe, and the glass skin.

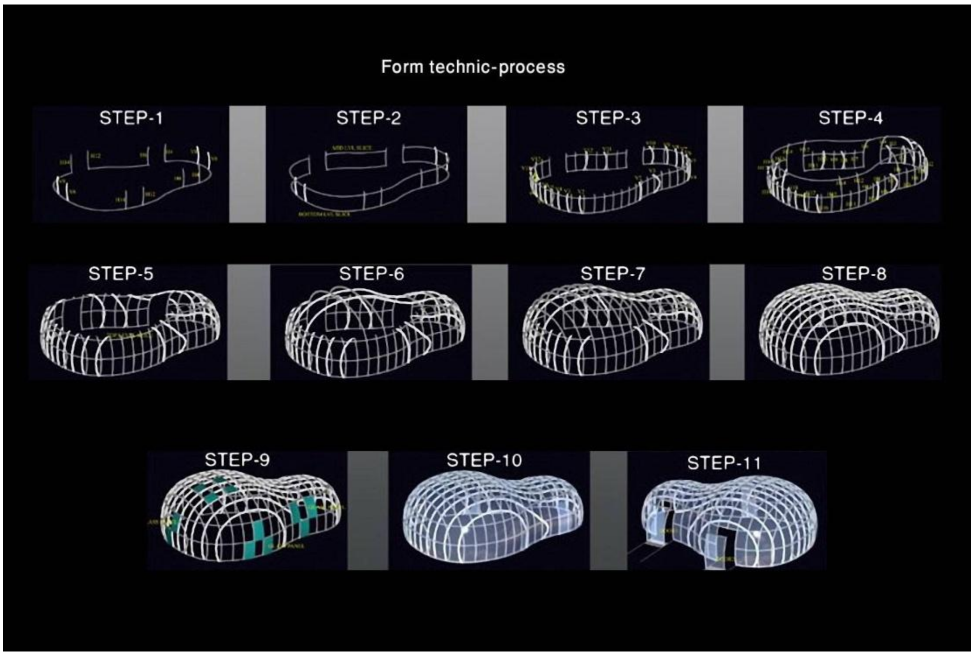


Figure 214: The process of form modeling by using NURBS method.

Here as a self-study, it is supposed to understand how such technique could be managed. Thus; the study made a practical work by using the technique of NURBS to recreate the same form of BMW pavilion by using the 3dmax software. The following figures illustrate the personal work of creating Franken's form "BMW pavilion" which supports the aims of the thesis. Figures (215, 216, 217).

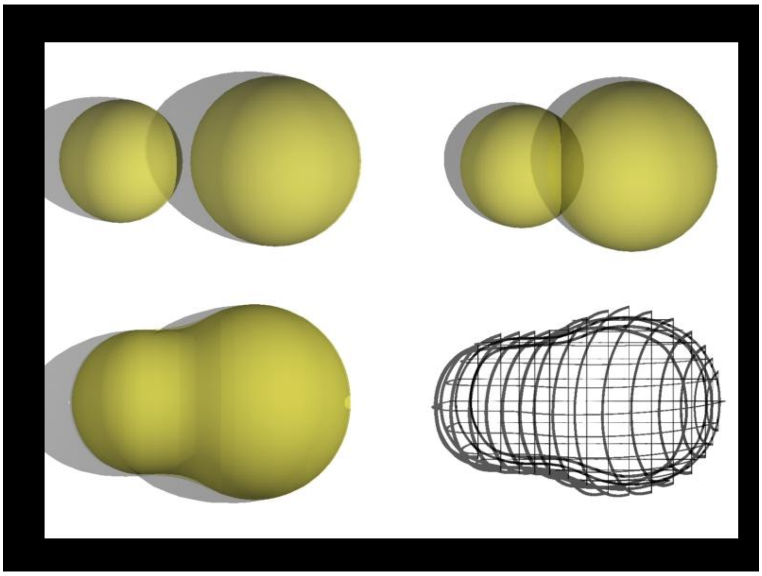


Figure 215: Generating the form using NURBS, Boolean union and mesh method.

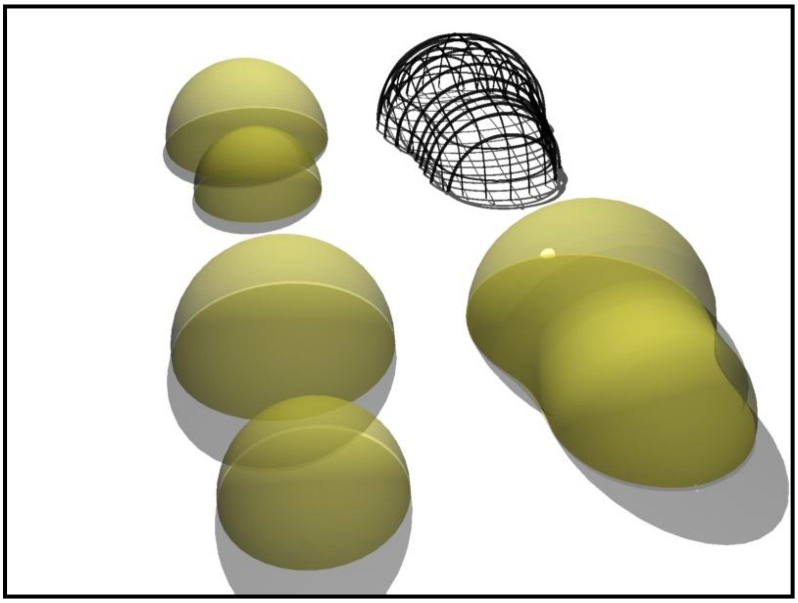


Figure 216: The three dimensional view of the generated form.

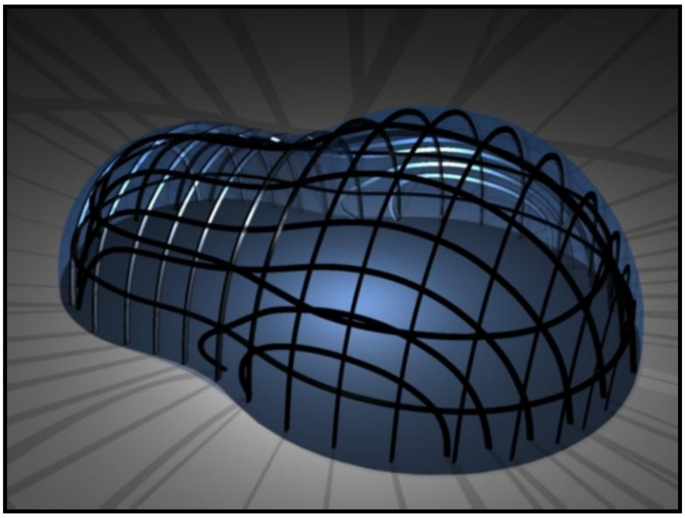


Figure 217: The wire frame-mesh structure and final form.

After the main form has been regenerated by computer techniques the next step before preparing the final components for the fabrication machines, he tested the resulted form physically by rapid prototyping (RP) process (figure 218).

Figure 218: The physical model of the wire framed form.
(Source: http://www.europaconcorsi.com/db/pub/images/5568/508123499.jpg)

7.2.3. Structure details

Simply; the structure components can be divided into two elements; the wireframe structure (metal) and the skin glass.

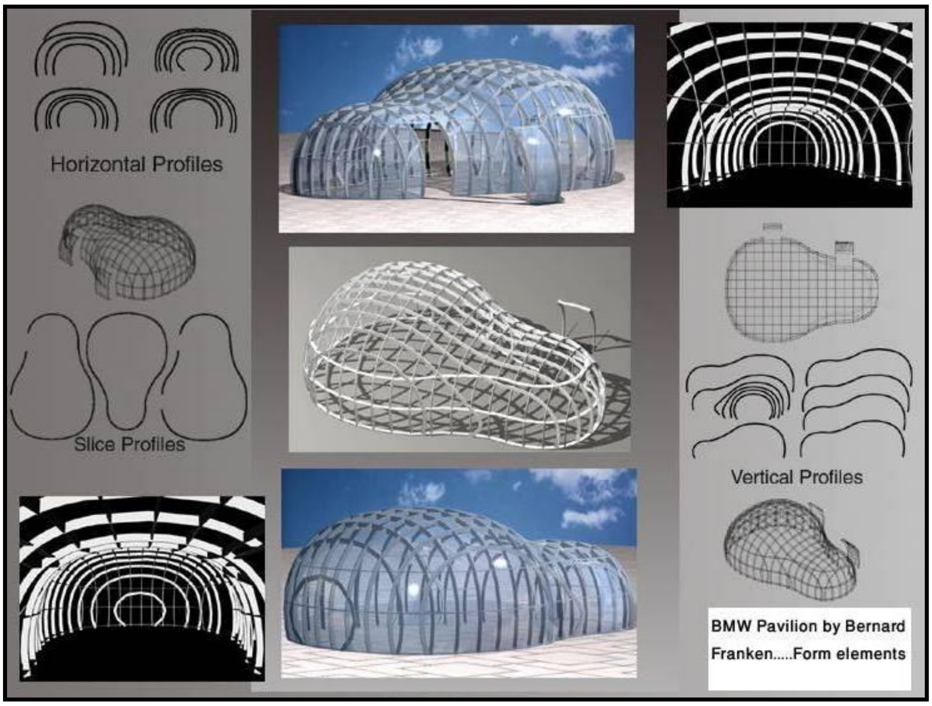


Figure 219: The individual elements of the main form.

7.2.4. Construction Process

After defining the type of materials for each component such as wireframe structure (metal) and the (glass) for the skin, each part will be precisely coded in file formatted (STL) including all the parts information and dimensions which will be send to the computer numerical controlling machines (CNC) laser cutter and bending machines that start numerically cutting, heating and bending the structure elements such as the wireframe steel bars (figure 220). Additionally; for the production of the laminated glass panels with complex curvilinear surfaces, the double curved surfaces (glass) was "approximated by arrays of height-adjustable, numerically controlled pins which used for the production of molded glass" (Kolarevic Branko, 2000). For instance; the shape of the curved glass sheet was fabricated by numerically controlled milling machine that shaped the wooden mould where then the glass was heated over the mould to achieve the required curved surface (figure 221).

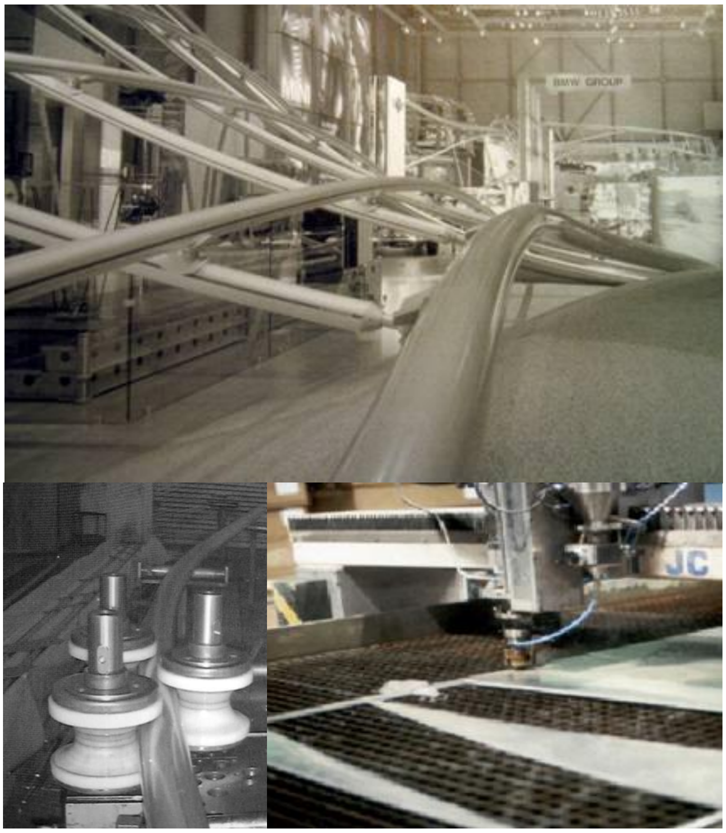


Figure 220: Cutting, twisting, and bending the structure frames.

(Source: http://lapa.epfl.ch/downloads/programming_as_design_method.ppt.)

Figure 221: Cutting the shell pieces of the exterior cover.

(Source: http://lapa.epfl.ch/downloads/programming_as_design_method.ppt.)

After the structure pieces have been prefabricated by the CNC machines, the final step will be assembling the fabricated elements on site. The following figures showing the assembling process of the structure components (Figures 222, 223).

Figure 222: Collecting the structure frames.

(Source: http://www.europaconcorsi.com/db/pub/images/5568/707966270.jpg)

Figure 223: Finishing the final details.

(Source: http://www.europaconcorsi.com)

7.3. Case (3):

Dynaform BMW, Germany, by ABB Architekten Bernhard Franken

The main form “Dynaform” consists of “16 pieces” of different futuristic steel posts. 16 individual membrane sheets were processed to a roof area of “6.500m²”. The type of materials used was the “PVC-coated polyester fabric type IV”. To reach the optical requirements of the structure, the membranes were provided with “8.000 pieces of specially designed clamping systems and gimbaled supports”. These were connected to the girders under the pretension required in an uniaxial way and free of folds, in order to avoid “saddle” areas between the girders. The facade of the building is covered by a “one-layered printed Hostaflon ETFE membrane” kept to its convex shape by means of pretension laths. Then; the edges and entrance sides are covered with large “double-layered Hostaflon ETFE areas in a vacuum”, in order to reach a new convex appearance [32].

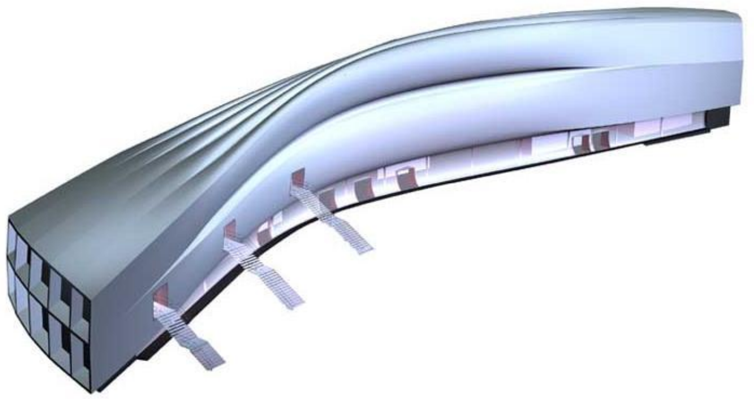


Figure 224: Digital model of the International Automobile Exhibition in Frankfurt (IAA 2001).
(Source: http://www.franken-architekten.de/)

7.3.1. Design process

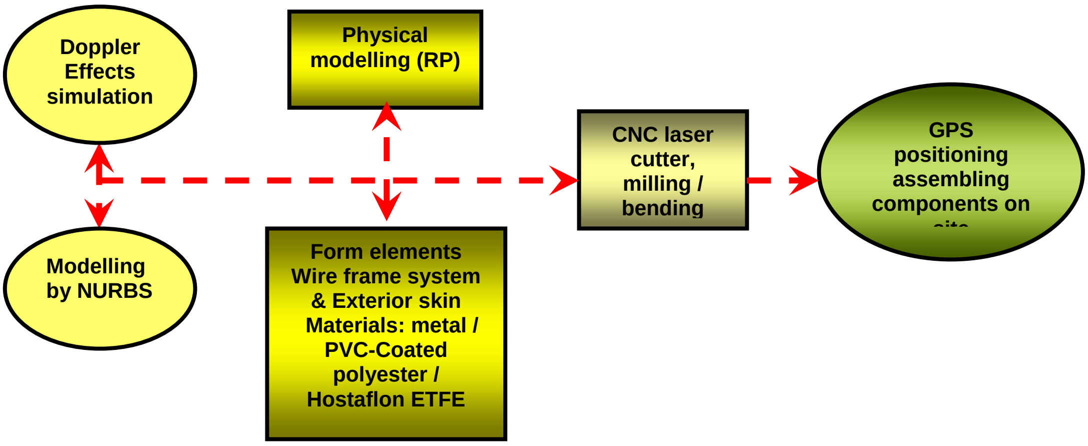


Figure 225: Bernard Franken Design Process of Dynaform BMW.

They accelerated the space around the automobiles to conjure up (bring to mind) the feeling of motion. Using the Doppler effect had given the choice of at which point during a force field simulation it should be pressed the stop button to select that particular design or whether this moment is arbitrary. The overlapping of spatially translated Doppler effects and the surrounding forces were used as the basis for the computer calculated building design (Figure 226).

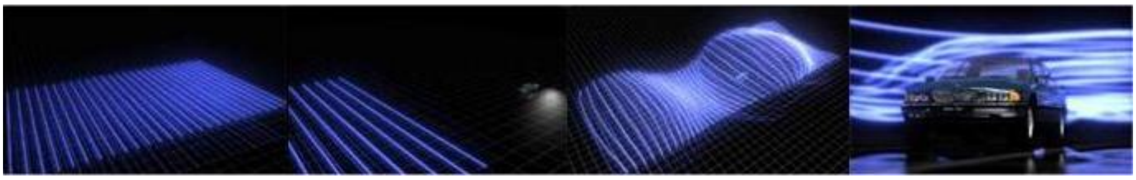


Figure 226: The accelerated space around the automobiles to invoke the feeling of motion.

(Source: http://www.franken-architekten.de/)

By overlapping the environmental forces and Doppler effects, they created the dynaform as they call it; which means (dynamic form) (figure 227).

“It is indeed arbitrary, for as in every other design method we must apply our understanding of form to decide which variation of the design offers us the most possibilities.” *Bernhard Franken, 2001.*

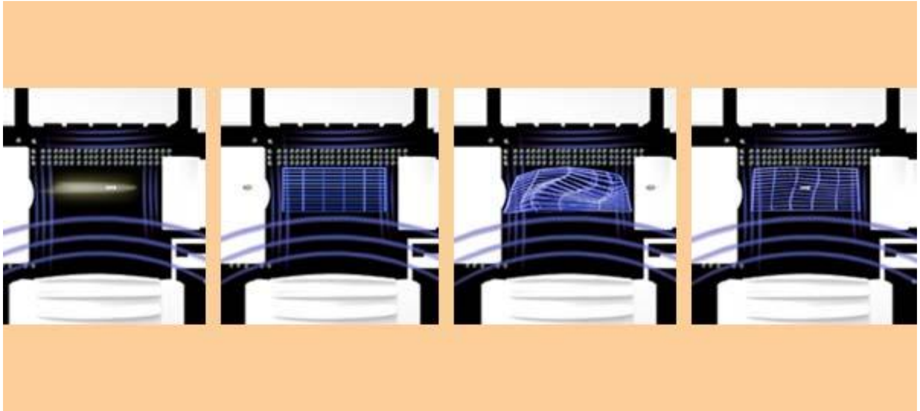


Figure 227: The force field simulation of the design concept.
(Source: http://www.franken-architekten.de/)

“Resulting from parametrical form generation with the Software MAYA is a volume deformed by perimeter conditions and the process. Gradually the stack of square tubes at both ends is transformed to the round sections in the middle. The finite elements calculation shows resulting forces that have to be neutralized. The curve is a result of the force field of the neighboring Fair Hall. Since ultimately a building skin is required for use as a fair hall, we trimmed the boundary layer from the outer tubes and used the computer to create connecting surfaces between the resulting strips.” (ABB Architekten Bernhard Franken) [33]. The physical models then built from the data files with detailed structures but without skin to express the precise dimension of the structure elements. The models were so convincing that it was decided to seek a method of translating the mill cut into a large scale.

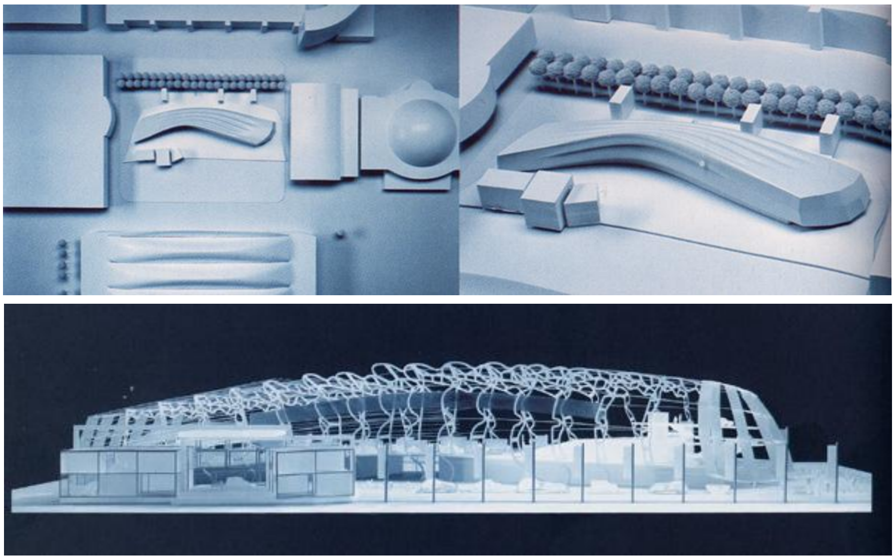


Figure 228: The detailed structures model of the main form.

(Source: http://lapa.epfl.ch/downloads/programming_as_design_method.ppt.)

7.3.2. Structure Elements:

1- The single member part:

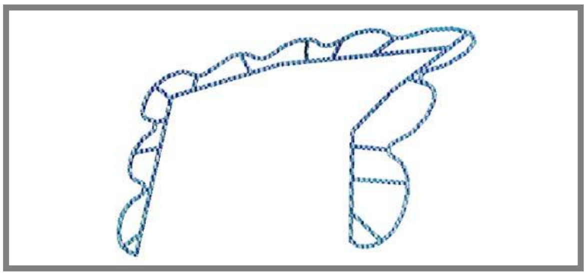


Figure 229: The single member part.

(Source: http://covertex.de/projekte)

2- The 16 individual membrane sheets:

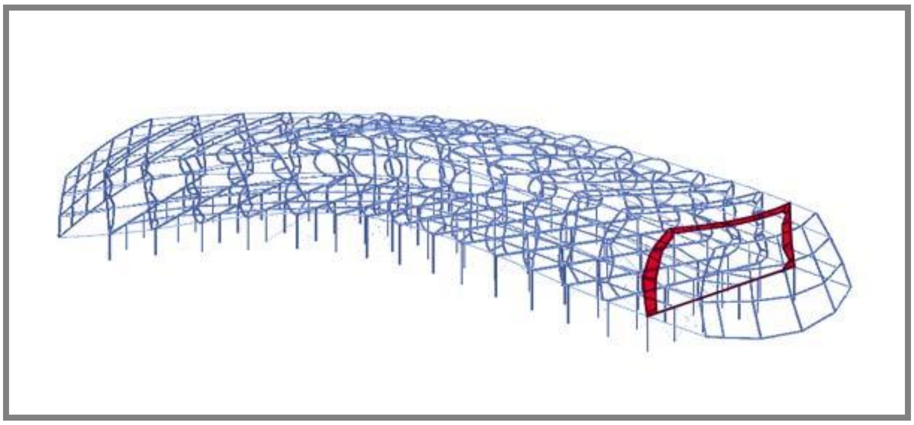


Figure 230: The 16 individual membrane sheets.

(Source: http://covertex.de/projekte)

3- The outer skin of the structure:

Figure 231: The outer skin of the structure.

(Source: http://www.europaconcorsi.com/db/pub/images/5569/1187955966.jpg)

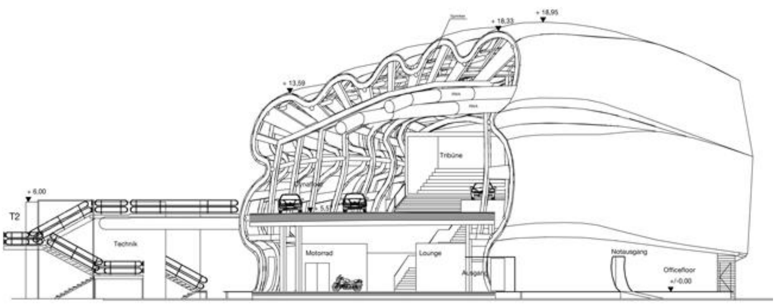


Figure 232: Cross section showing all the details and structure elements.

(Source: http://www.europaconcorsi.com/db/pub/images/5569/825818420.jpg)

7.3.3. Fabrication Process:

Figure 233: Using the digital machines for cutting the edges of the wire frames pieces.

(Source: http://www.europaconcorsi.com/db/pub/images/5569/1325414589.jpg)

After the section frames have been milled, cut and bent by the (CNC) machines (figure 233), they will be welded together to complete the section shape of each frame. This step will be done at the digital studio machines (figure 234).

Figure 234: The sectional frames “structure” pieces welding together.

(Source: http://www.europaconcorsi.com/db/pub/images/5569/424573179.jpg)

The next step after completing all the structure frames is that ordering the frames to the site and connecting them together as designed; this step called "assembly" (figure 235, 236).

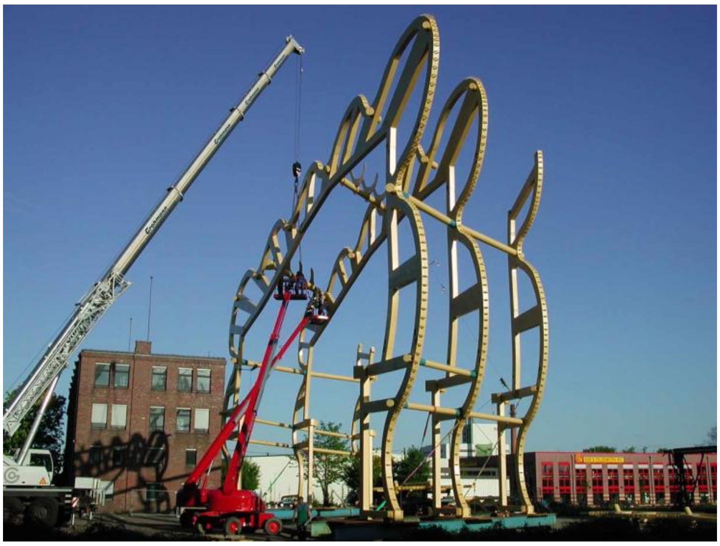


Figure 235: Reordering the structure elements at the site.

(Source: http://www.europaconcorsi.com/db/pub/images/5569/82032901.jpg)

Figure 236: The main structure is finished here.

(Source: http://www.europaconcorsi.com/db/pub/images/5569/884988473.jpg)

The final step is covering the structure frames by the skin cover which is the “PVC-coated polyester fabric type IV” [34].

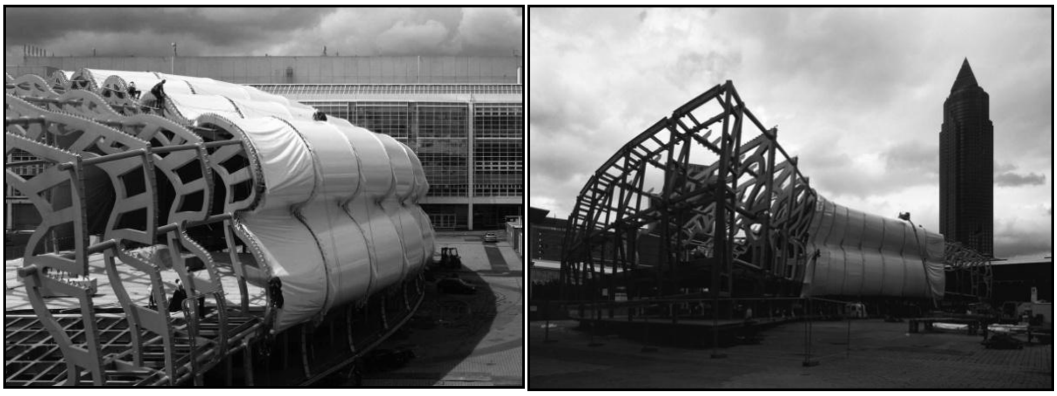


Figure 237: Covering the structure by the skin.

(Source: http://www.europaconcorsi.com/db/pub/images/5569/659201419.jpg)

Figure 238: The completed form.

(Source: http://www.europaconcorsi.com/db/pub/images/5569/1537317923.jpg)

7.4. Case (4):

Water Pavilion (H2O Expo), Netherlands, By NOX

"Liquid architecture is not the mimesis of natural fluids in architecture" (Marcos Novak, 1993). First and foremost it is a liquidizing of everything that has traditionally been crystalline and solid in architecture. Liquid architecture is always about trying to connect one act to another, about putting a virus in the program itself, about the hyperbolic linking of events, where every object and every event can have unforeseen and unprogramed effects. In other words; no function, no object can remain isolated; everything is involved in a continual process of transformation into the other.

Figure 239: Water pavilion or H2O Expo exterior view.

(Source: http://www.europaconcorsi.com/db/pub/scheda.php?id=4539)

7.4.1. Design Concept (Liquidizing Form)

"H_2O expo" by NOX, as named but generally known as the "water pavilion" in the Netherlands, was built in 1997, and has been completely seized by the concept of the "liquid", not only in its shape and its use of materials, but also because the interior environment tries to bring about a "prototypical merging of hardware, software and wetware" (Ineke Schwartz, 1997).

The building's geometry is generated through "interactive transformation". It starts with a simple tube made up of ellipses, which are rescaled according to the internal programme, then deformed according to "site influences", such as "wind direction, sand dunes and flows of incoming visitors". The entrance begins with a small ellipse on its vertical axis and ends, some 60 meters further on, with a larger ellipse on its horizontal axis. In between, the building twists and turns. Since the sections are continuous and floor blends into wall and wall into ceiling. "The visitors of the building must act like water to pass through the building". The set of operations as follows: "elliptical tube, scaling of tube according to programme, twisting according to exterior forces, insertion of ground level, deformation of ground surface" (Lars Spuybroek, 2004).

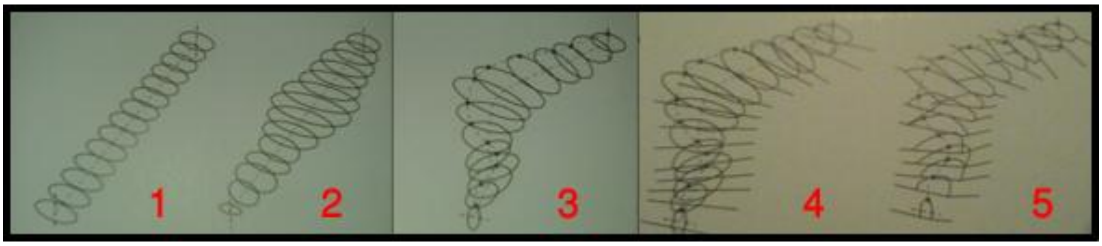


Figure 240: The transformation process of an ellipse into three dimensional form, (Lars Spuybroek, 2004)

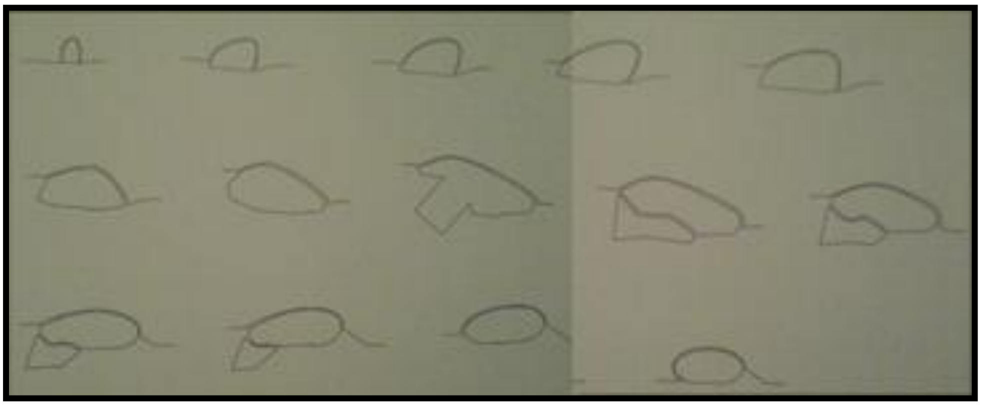


Figure 241: Transformation of the ellipses shape and the ground surface, (Lars Spuybroek, 2004)

7.4.2. Design Process

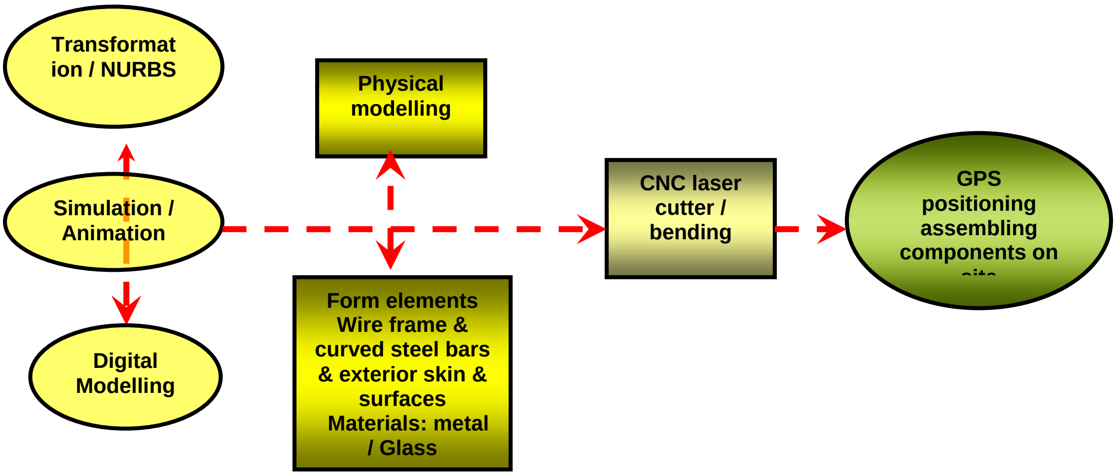


Figure 242: NOX Design Process of H2O Expo.

The complex structure of H_2O developed and modeled on "high-end workstations advanced animation and simulation software", which is a braid of sixteen splines that are shaped like "elongated worm" of steel ellipses and semicircles. Within the 3D modeling software used to design and generate the pavilion, the splines are defined as active and reactive forms; unlike lines which are traces of actions. When the splines are pulled in their virtual state, they deformed in simultaneous action according to the parameters determined by programming "scripts and routines" developed by NOX. In the reality this creates an environment in which "floor blend into wall, wall into ceiling and where nothing is horizontal" (Peter Zellner, 1999).

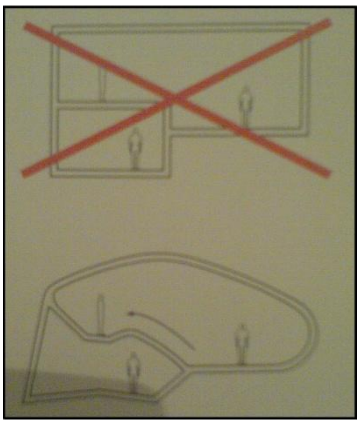


Figure 243: The logic of transformation on which the components are blended together, (Lars Spuybroek, 2004)

After the main shape has been transformed into several sectional ellipses which transformed according to the ground action, the final form created by connecting each section to another using NURBS method to have the exterior skin done. Then the digital model was simulated using computer software as well as the physical model.

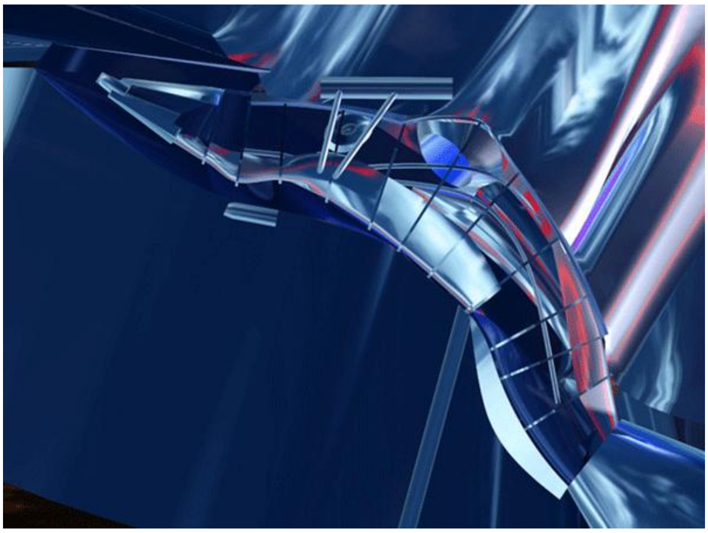


Figure 244: Three dimensional model of H2O Expo, (Peter Zellner, 1999)

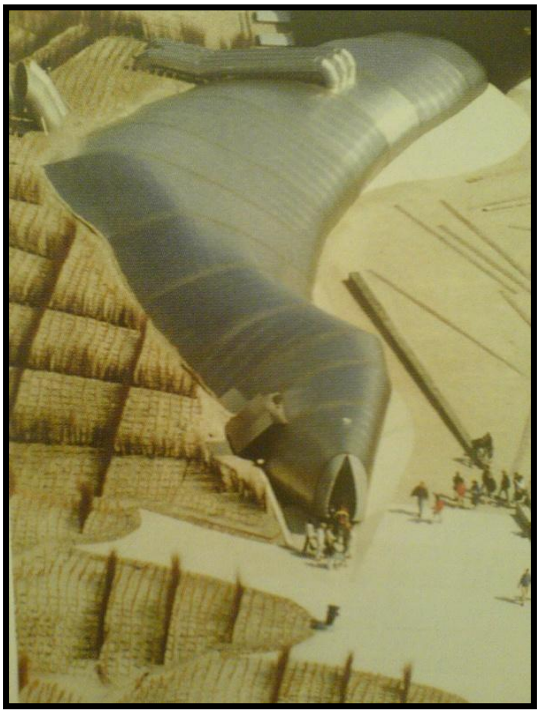


Figure 245: Physical model of H2O Expo, (Lars Spuybroek, 2004)

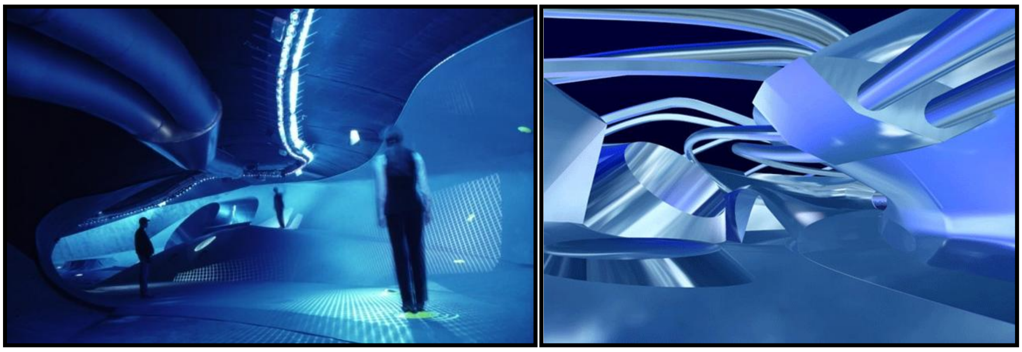


Figure 246: Three dimentional simulation.

(Source: http://www.europaconcorsi.com/db/pub/scheda.php?id=4539)

7.4.3. Structure Elements

The four main elements of the structure have been identified to prepare the final data for the fabrication process. The elements are namely:

- Wireframe structure.
- The curved steel sections.
- Exterior skin.
- Internal surfaces.

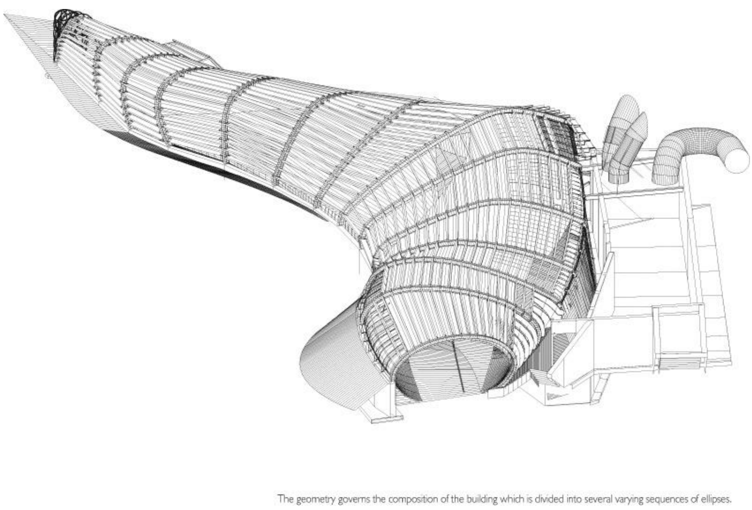


Figure 247: The geometry governs the composition of the building which is divided into several varying sequences of ellipses, (Lars Spuybroek, 2004)

7.4.4. Construction Process

As done in many recently fabrication process; after the structure information have been formatted the final file sent directly to the CNC machines that cuts, bent every part based on the dimensions given then the components assembled on the site for the final completion.

Figure 248: Wireframe steel structure of Water pavilion.

(Source: http://www.europaconcorsi.com/db/pub/scheda.php?id=4539)

Figure 249: The completed form indicates the outlines and exterior surfaces.

(Source: http://www.europaconcorsi.com/db/pub/architecture.php?id_scheda=4539&idimg=32460)

7.5. Case (5)

Sendai Mediatheque, Sendai city, by TOYO ITO

Figure 250: The physical model of Sendai Mediatheque, Tyo Ito

(Source: http://www.arch.columbia.edu/Students/Spring99/Stoltz.gary/cad.html)

7.5.1. Program and Concept

The idea of "Mediatheque" by Tyo Ito embodies the proposal of another new concept in architecture. The project started with an open competition held by Sendai City. The proposal consists of three elements of "plate", "tube" and "skin" which are the main elements of the building form. The "plates" are the six square slabs and they attempts to diagrammatically express different modes of communication between people and things. Whereas the "tube" referred to the thirteen-trees which are vertically penetrating the plates. They are the flexible structural members acting also as the vertical traffic line and as the space where energies (light, air, water, sound, etc.) and information flow. The presence of the tubes creates movements of "natural elements and of electrons" in the homogeneous spaces defined by the plates. Although by the "skin" Ito referred to the elements that separate the inside of the building from the outside. It particularly refers to the skin that surrounds the "machine spaces" located at the top and the bottom of the building and the "double-skinned" facade facing the main street [35].

7.5.2. Structure Elements

The structure consisting of three main elements, “Plate, Tube and Skin”. the floors are the horizontal lines set at irregular heights; the tubes are “transparent lattices” snaking through the building; and the vertical glass skin hangs from the floor plates [36].

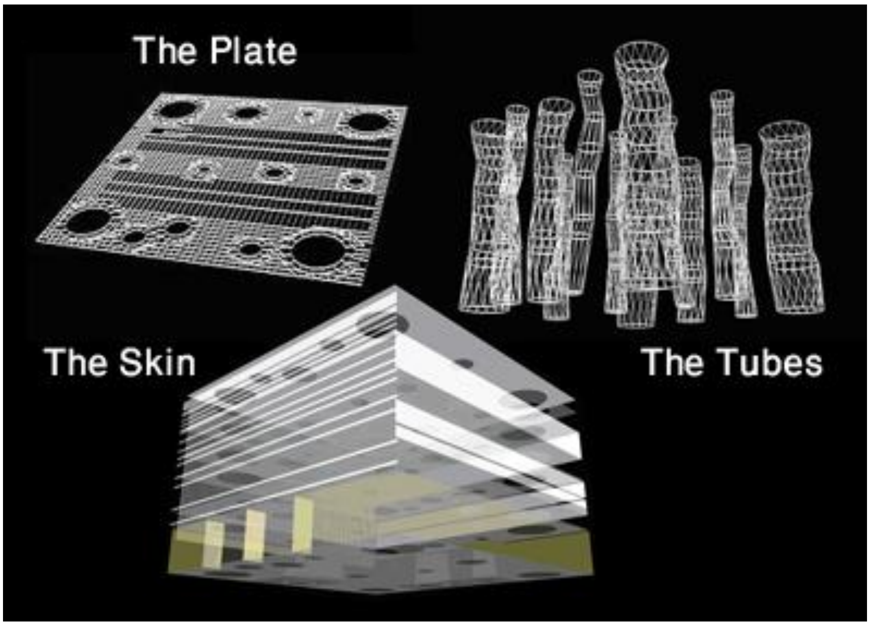


Figure 251: The structure elements; Plate, Tube and Skin.

(Source: http://www.arch.columbia.edu/Students/Spring99/Stoltz.gary/cad.html)

7.5.3. Design Process

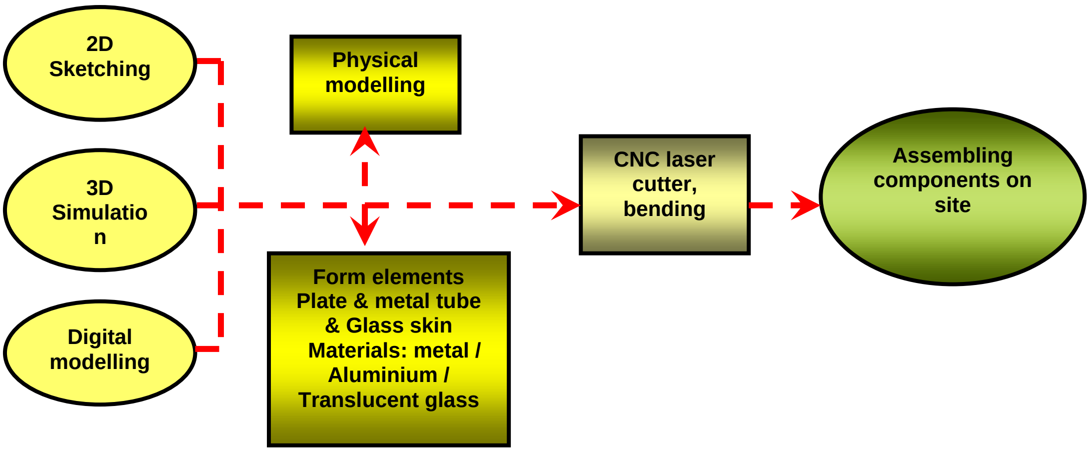


Figure 252: Toyo Ito Design Process of Sendai Mediatheque

Several layout variations were produced for each floor plan. Ito continually tested his design against the “ideas and images” which generated it. He worked with graphics firm that structurally used “computer simulation” to create the sequences generated from simple plan, elevation and section drawings. By using the animation technique he tried to enhancing the “perception of form”. Furthermore; he gave the concept more three-dimensional expression by making digital and physical models. Digitally; the tubes were generated by using “slicing and lattice techniques”; at the same time the typical tube shape was transformed from being cylindrical to take the irregularity of free shapes which transformed the main shape of the tube to snaking one. Then he physically prototyping an “experimental model for testing the resulted form” which then separated into several units that made in digital file format for digital fabrication process [37].

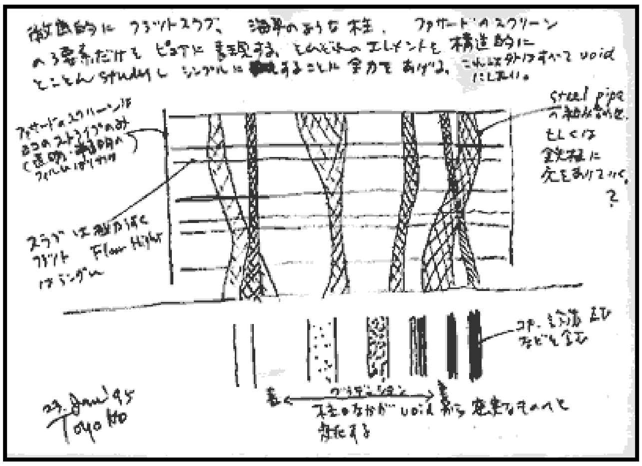


Figure 253: Toyo Ito’s Hand sketching

(Source: http://www.um.u-tokyo.ac.jp/publish_db/1997VA/english/virtual/05.html)

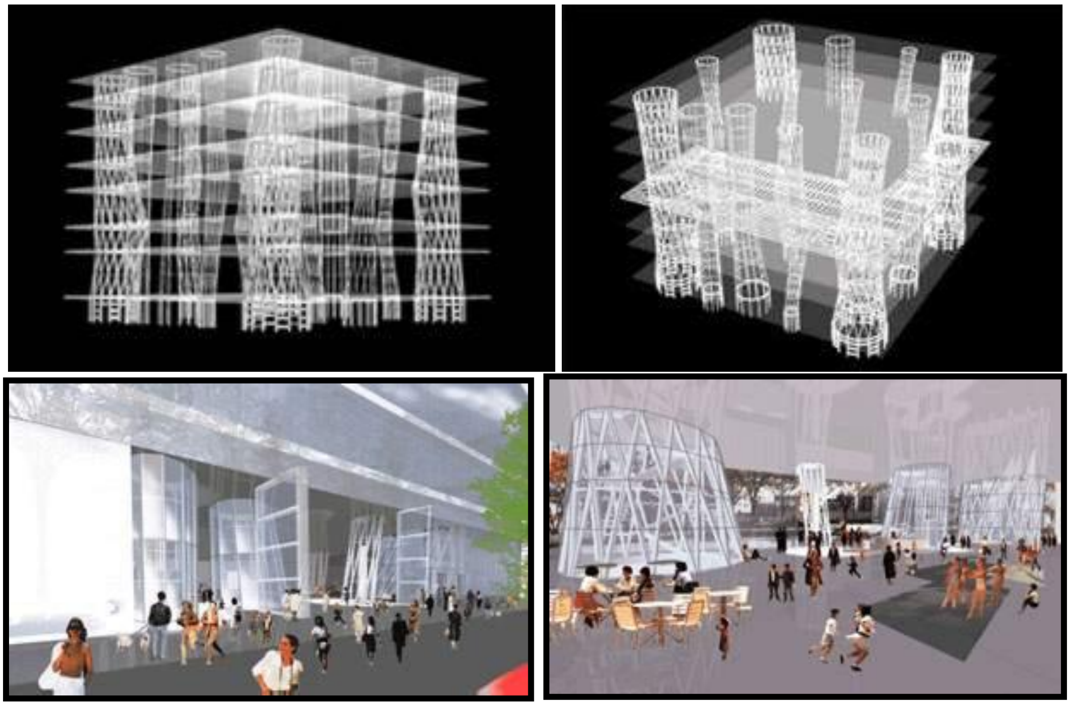


Figure 254: Three dimensional modeling of Sendai Mediatheque.

(Source: http://www.um.u-tokyo.ac.jp/publish_db/1997VA/english/virtual/05.html)

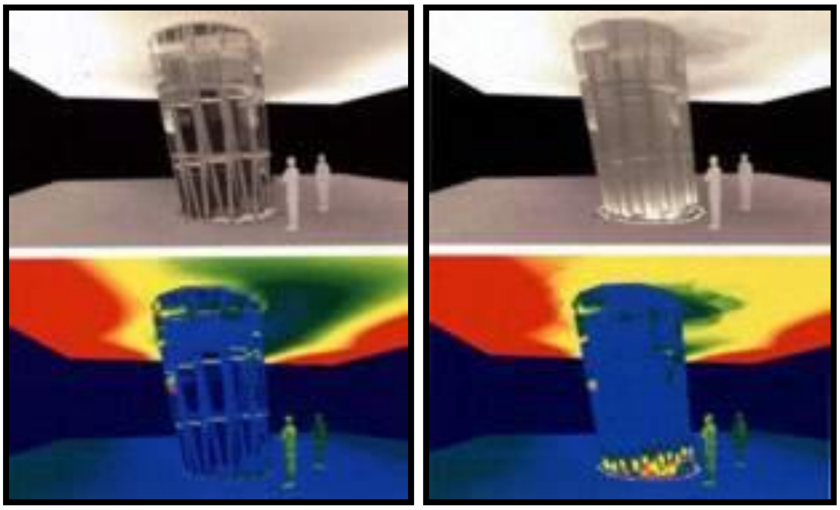


Figure 255: Computer simulation of Sendai Mediatheque.

(Source: http://www.um.u-tokyo.ac.jp/publish_db/1997VA/english/virtual/05.html)

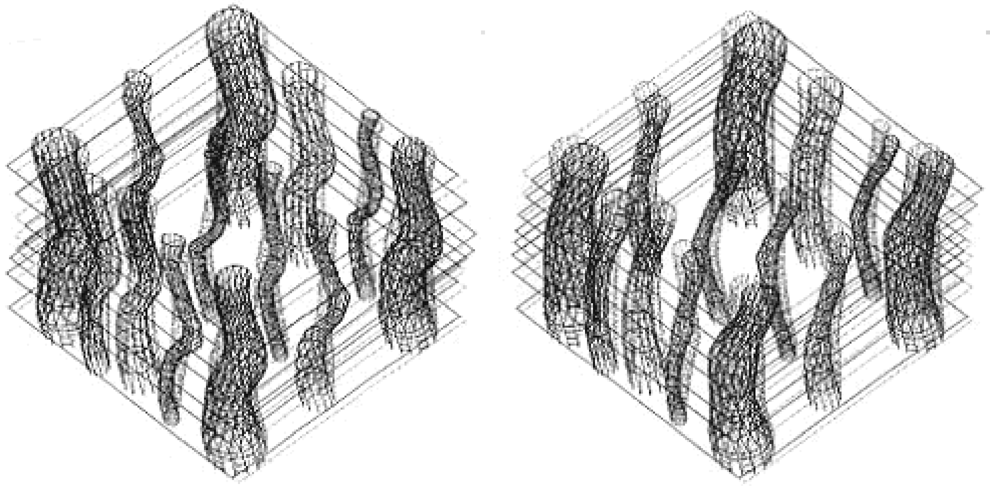


Figure 256: Transformation of the tubes.

(Source: http://www.um.u-tokyo.ac.jp/publish_db/1997VA/english/virtual/05.html)

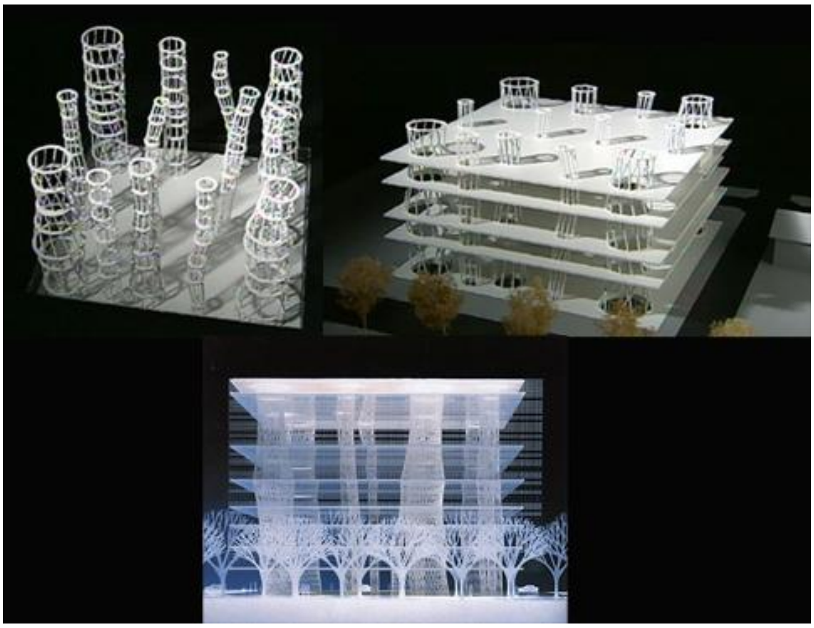


Figure 257: Physical prototyping of Sendai Mediatheque.

(Source: http://www.arte-boutique.fr)

7.5.4. Construction Process

Basically; the process of construction was done totally on site except for preparing the tube bars which are needed to be bent in CNC machine as well as holing the plates by CNC laser cutter that cut the different hole sizes precisely for the accuracy when they superimposed over each others. The types of materials used for tube meshes were metal, aluminum panels, and translucent glass for the exterior skin.

Figure 258: During the construction process of Sendai Mediatheque, positioning and assembling the tubes.

(Source: http://sendai.cool.ne.jp/pbx/first.html)

Figure 259: Constructing the façades of Sendai Mediatheque

(Source: http://sendai.cool.ne.jp/pbx/first.html)

Figure 260: Completed form of Sendai Mediatheque.

(Source: http://sendai.cool.ne.jp/pbx/first.html)

7.6. Case (6):

The acoustic barrier, Netherlands, by Kas Oosterhuis

7.6.1. Design Concept

The purpose is briefly to combine the 1.5km long acoustic barrier with an industrial building of 5000m2 · The concept of the acoustic barrier is to design with the speed of passing traffic since the building is seen from the perspective of the driver ·

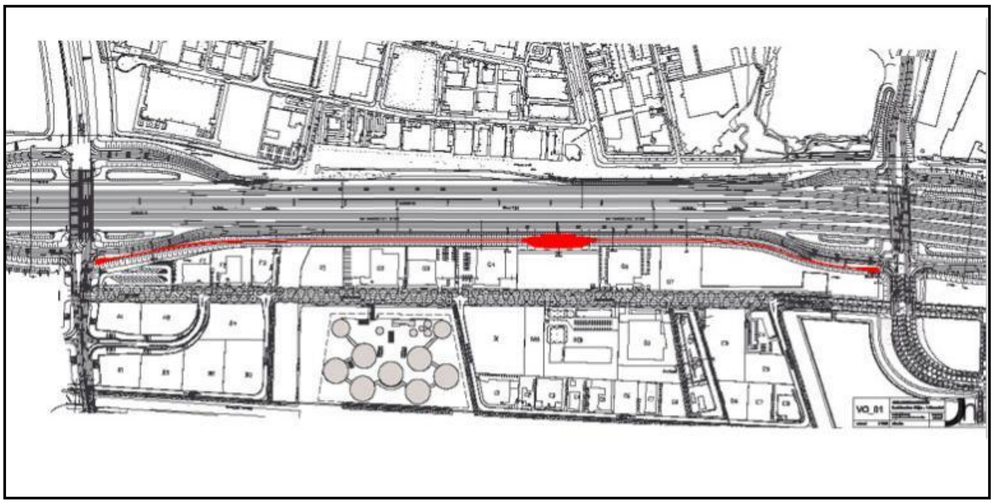


Figure 261: Site view the acoustic barrier.
(Source: http://www.oosterhuis.nl)

The Hessing showroom: the most striking design principle of the "Hessing showroom" (figure 262), which is immersed in the long stretched volume of the acoustic barrier, is the use of "long continuous lines, which do not have an explicit beginning and not an abrupt end". Further; the top line goes up, and the bottom line goes further down, thus creating a great space for the showrooms which is a "horizontal cathedral for cars" [38].

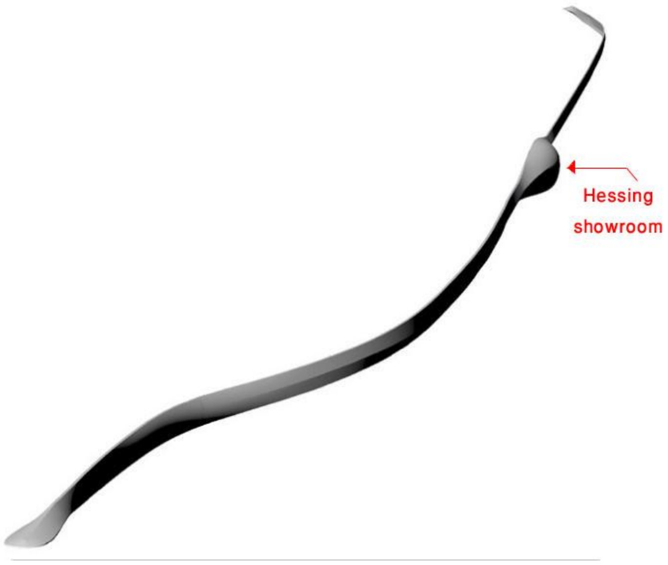


Figure 262: The Hessing showroom, Oosterhuis associates.

(Source: http://www.oosterhuis.nl)

Figure 263: The real view from the traffic side, Oosterhuis associates.

(Source: http://www.oosterhuis.nl)

7.6.2. Design Process

The team of Oosterhuis has taken three factors as the bases of the design process. Those factors are using "the smooth set of curves with NURBS method" to react with the context and describing the geometry. Secondly for generating their concept both visually and physically they have brought new process which based on parametric design that using "scripting data" for defining the geometrical shape. The third factor is establishing "networked machines" communicating with each other to produce an endless variety of different building elements which is called "peer-to-peer network of machines" [39].

"Collaborative design relies completely on the uncompromised parametric basis for the design · If not built parametrically you can not play with the parameters, and you are not able to interfere with it · You would not be able to communicate smoothly with the 3d model and the project database, neither in the design process nor in the life-cycle of the environment"... Kas Oosterhuis [40].

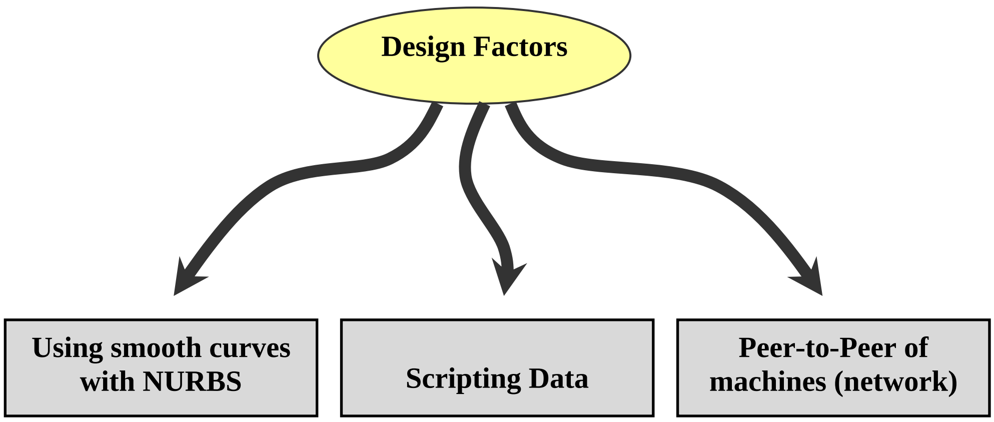


Figure 264: The design factors.

Working with parametric models facilitated a possible and meaningful interaction between the designers, builders, clients and users because every part of the project can be perceived before any construction operation starts. Simply; the concept does not describe exact values, but parametric relations between "height, width and length" [41]. Kas Oosterhuis explained the parametric design as "parametric design for the construction details and for the cladding details. Basically this means that there is one principal detail, and that detail appears in a multitude of different angles, dimensions and thicknesses. The parametric detail is scripted like a formula, while the parameters change from one position to the other. No detail has similar parameters, but they build upon the same formula. This detail is designed to suit all different faces of the building. Roof, floor and facade are treated the same. Front and back, left and right are treated equal. There is no behind, all sides are up front. In this sense parametrically based architecture displays a huge correspondence to the design of industrial objects" [42]. Briefly; the following diagram illustrates the Kas Oosterhuis' design process.

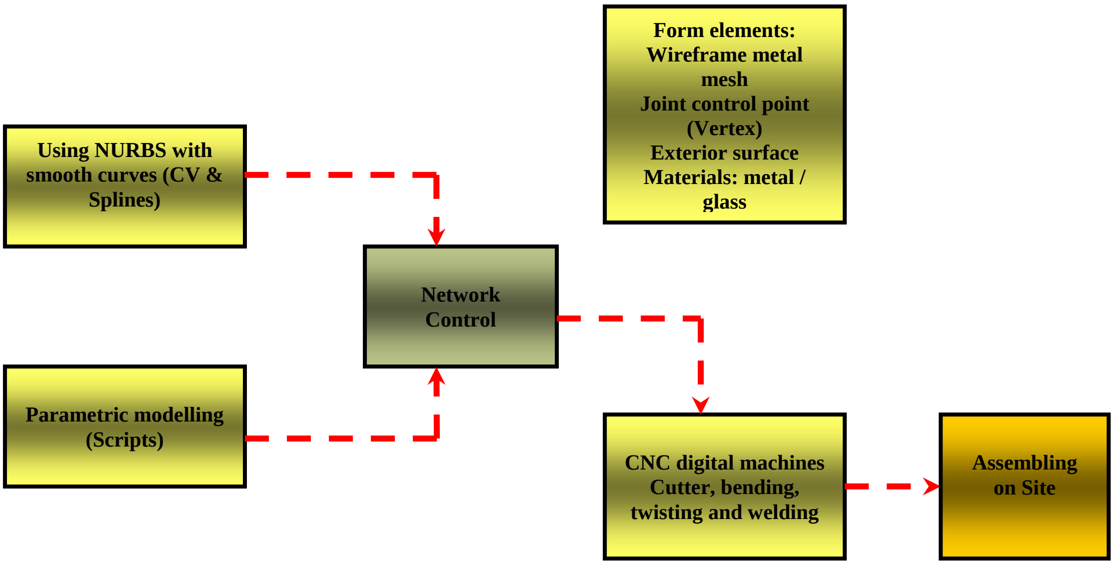


Figure 265: Oosterhuis associates' Design Process.

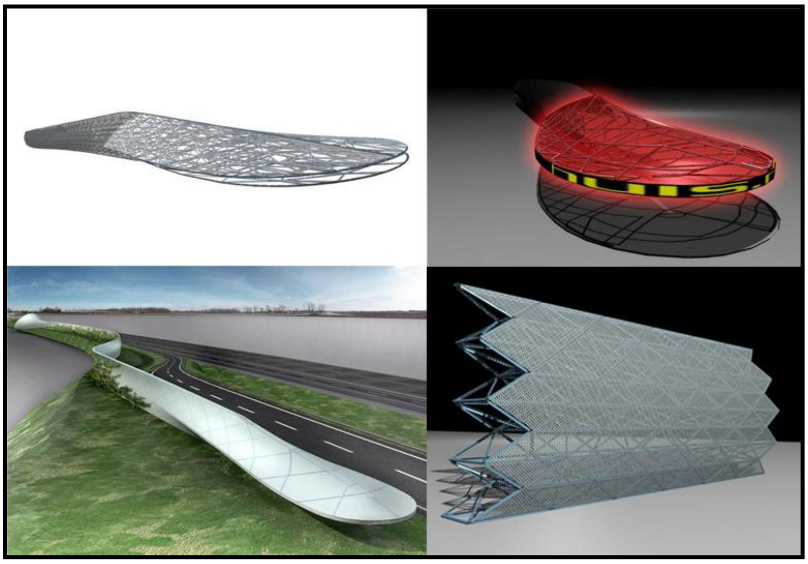


Figure 266: Using NURBS for modeling, Oosterhuis associates.

(Source: http://www.oosterhuis.nl)

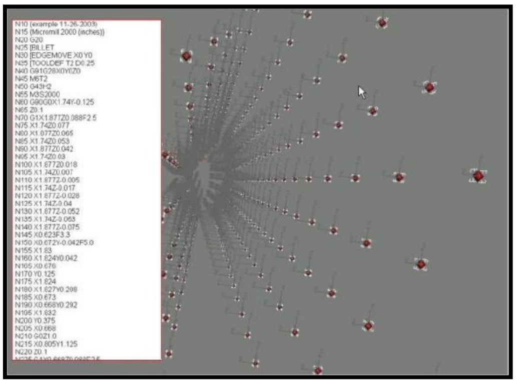


Figure 267: Using scripts for design generation

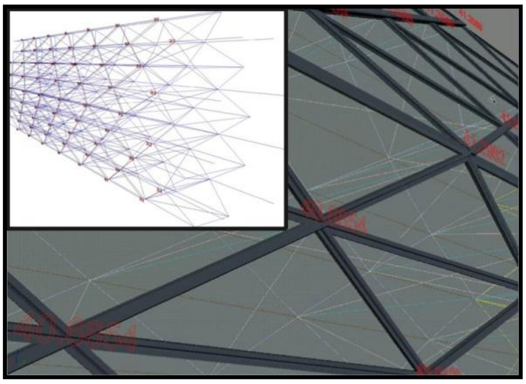


Figure 268: defining the geometrical data of the control points (Vertex).

(Source: http://www.oosterhuis.nl)

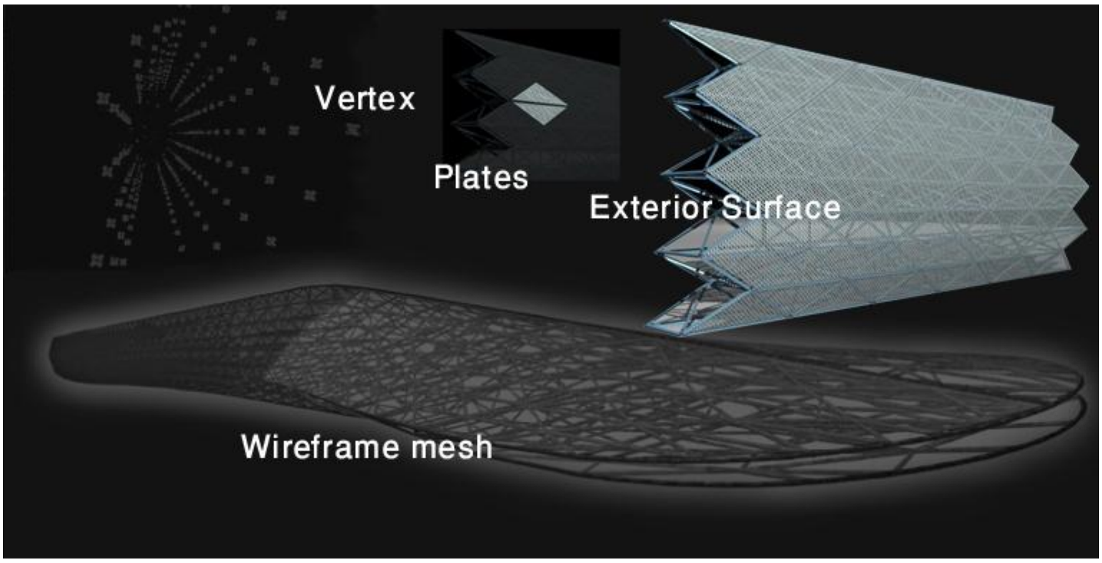


Figure 269: Defining the structure elements.

(Source: http://www.oosterhuis.nl)

7.6.3. Construction process

After finishing the structure components parametrically, they prepare the work in STL file format that the CNC machines accept then they send the file to the machines according to every part modification and data. Laser cutter, bending, twisting and welding are the major operations during the fabrication process. So briefly; prefabricating the structure parts “wireframe” and using networked computer numerical control, then make the combination on the site this is the main fabrication process of the acoustic barrier.

Figure 270: Fabrication tools and basic structure elements

(Source: http://www.oosterhuis.nl)

Figure 271: Real view during the construction process.

(Source: http://www.oosterhuis.nl)

Figure 272: The completed form of acoustic barrier.

(Source: http://www.oosterhuis.nl)

7.7. Case (7):

Selfridges Birmingham, Birmingham, UK, by Future Systems Association

7.7.1. Project description

SELFRIDGES located at Birmingham city was designed by future systems association and completed in 2003. It's a three-dimensionally curvaceous form "hugs the dramatic incline of the newly redeveloped bull ring site as it moves like a shimmering silver wave and drops down to St Martin's square below" [43]. The concept of the Selfridges's form can be considered as many new concepts that based totally in its free shape. The study has taken this project as an example to support the thesis issue.

Figure 273: SELFRIDGES BIRMINGHAM, 2003, UK, Future systems Association, (Michael .S, Philip .B and Vincent .H, 2004)

7.7.2. Design Concept

Future Systems' vision was a building form that would fit the contextually diverse site whilst embracing Selfridges' demand for an internally-focused, windowless box. The resulting unique façade gives scale, texture, and an accentuation of the building curvature (figure 274).

Figure 274: The façade's skin.

(Source: http://www.virtualbrum.co.uk/selfridges2.htm)

The fluidity of shape recalls the fall of fabric or the soft lines of a body, rises from the ground and gently billows outwards before being drawn in at a kind of "waistline". It then curves out again and over to form the roof, in one continuous movement. The skin is made up of thousands of "aluminum discs, creating a fine, lustrous grain like the scales of a snake dress" [44].

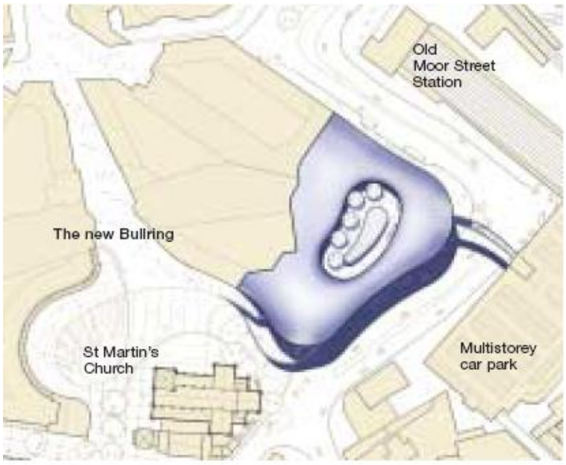


Figure 275: Location plan of SELFRIDGES BIRMINGHAM.

(Source: http://www.virtualbrum.co.uk/selfridges2.htm)

7.7.3. Design Process

The process started from finding out the structural solution of the free-form skeleton and the building façade which is the structural steel frame. As the main concept of the building assimilated in the complicated free-form shape, CAD/CAM technology and mass customization were incorporated as a design solution. Thus; three dimensional modeling such as Rhinoceros and unique software application GSA was developed to produce the design patterns. By that way; it seems that no hand sketches were used in the early stage of the design process.

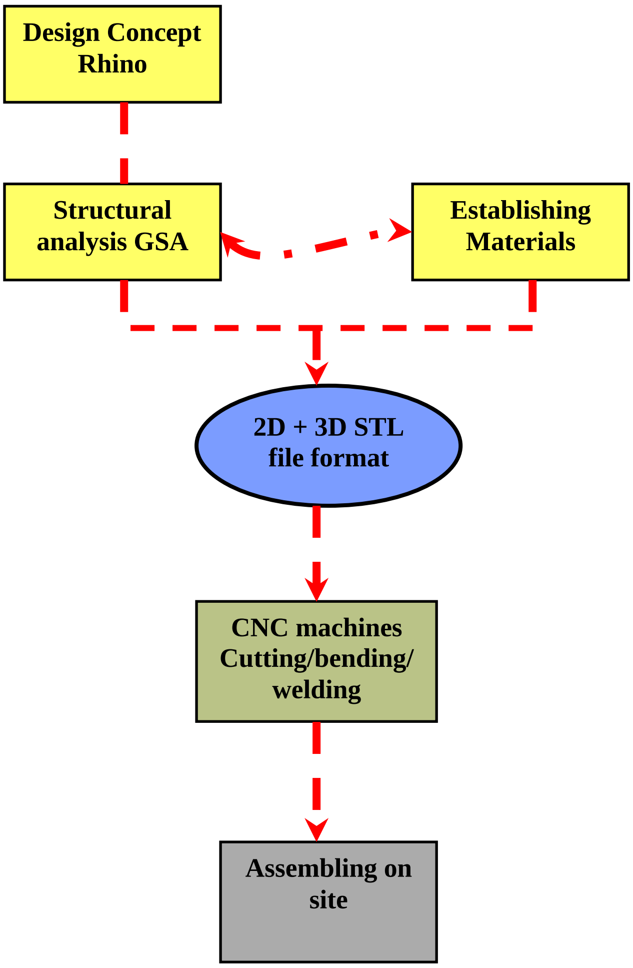


Figure 276: Future systems Association Design Process.

- The following figures showing the strategy of using GSA simulation a tool for the design analysis.

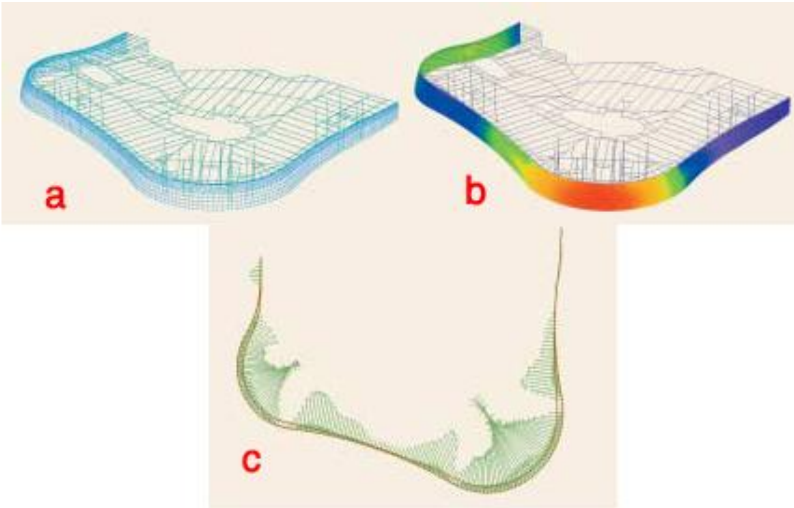


Figure 277: GSA analysis, (The Arup Journal 2005).

Figure 278 description

a) Combined floor frame/façade model used to study the composite behavior of the system.
b) Façade displacements around a typical storey ribbon under full loading, showing the extent to which the façade evens out the localized deflections of the supporting steel frame.
c) Forces on the restraint detail at the bottom of a storey ribbon under vertical loading. Wind forces only predominate in a few areas.

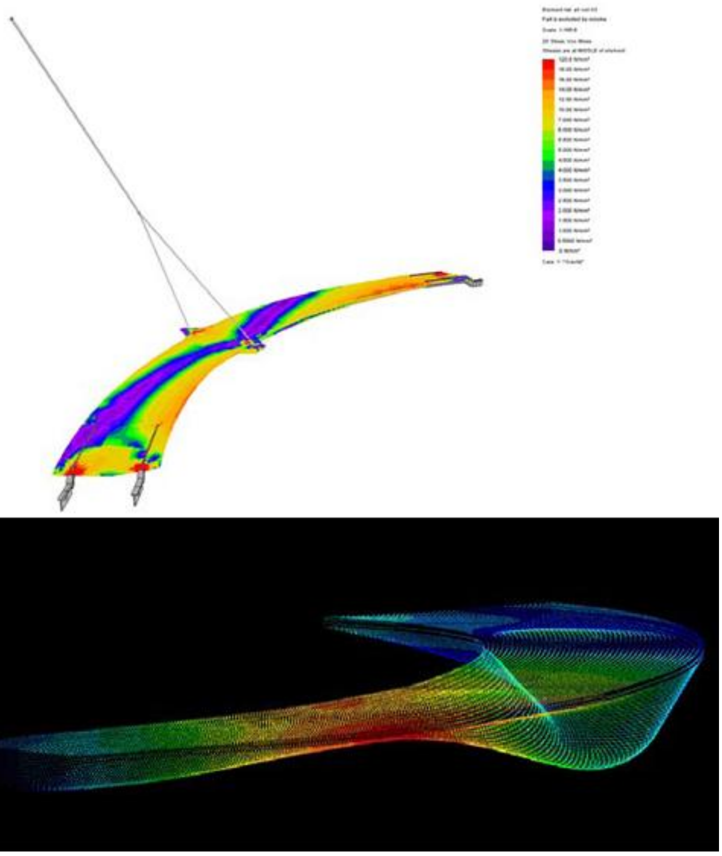


Figure 278: GSA analysis of the bridge structure, (The Arup Journal 2005).

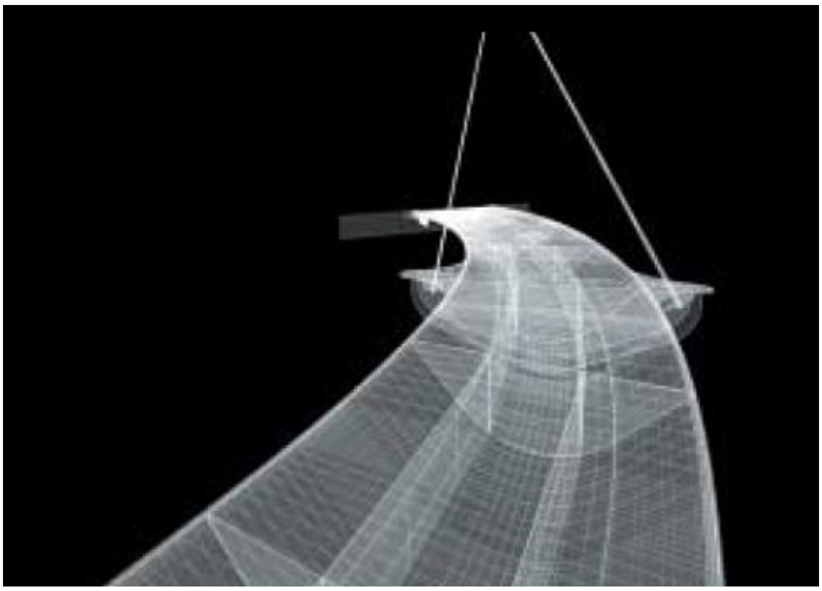


Figure 279: Rhino 3-D Model of the bridge, (The Arup Journal 2005).

As the plan shape of the building changes from floor to floor and the curvature of the plan layout, individually and strategically grid columns (regular and irregular grid) were placed to suit both the structural and architectural requirements.

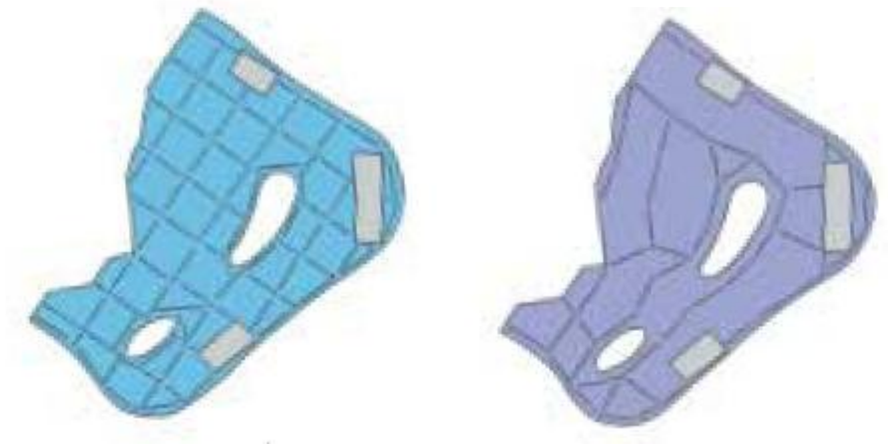


Figure 280: Conceptual column grid options: (left) Framing option 1: Regular column grid imposed on irregular plan & (right) Framing option 2: Irregular column grid, (The Arup Journal 2005).

7.7.4. Construction Process

The involvement of construction was manipulating the changeability of the plan shape from floor to floor to match the curvature of the envelope in section which requires secondary beams to cantilever from the perimeter column line by different distances around the slab edge and at each level. At the “waist” of the building the columns sit tight against the inside of the façade, whilst at the “hips” and “shoulders” the floor cantilevers to the façade by up to 4.5m, deemed to be the maximum practical limit and thus controlling the vertical curvature of the building. It was these relatively long spans and the lack of a “regular grid” that drove the design towards a “steel solution” (The Arup Journal, 2005)

Figure 281: Atrium steelwork, (The Arup Journal 2005).

Figure 282: External view of completed frame, (The Arup Journal 2005).

The lack of forming the curved geometry of the façade without incurring high construction costs presented one of the most complex design challenges. The varying curvature and non-developable shape of the building "precluded" efficient modularization of structural components or formwork, which prompted the team to look at more "homogeneous and unconventional methods of façade construction". Options such as "steel mullions, precast concrete, Ferro cement, and GRC" were investigated, but eventually "rejected in favor of sprayed concrete" (figure 283), which could be formed to the required geometry and sprayed to a thickness whereby it could hold its own shape and “resist wind loads” without the need for a supporting sub-frame (The Arup Journal, 2005).

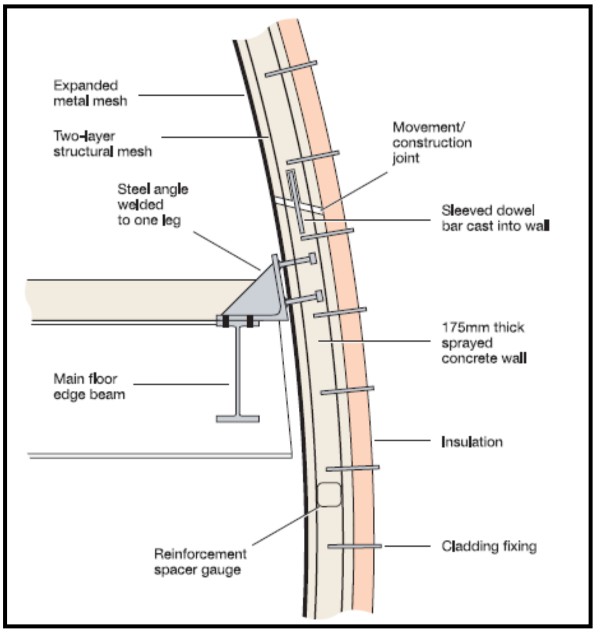


Figure 283: Indicative section through sprayed concrete wall, showing fixing detail, (The Arup Journal 2005).

Expanded metal mesh was used as “permanent formwork”, bent on site to the required curvature and held in position by an “adjustable scaffold system” supported on the floor slabs within the building. The chosen structural system divides the surface of the façade into “storey-height ribbons”. This avoids the problems of “supporting a 30m high concrete façade around the ground level”. window openings and off the edge of a retaining wall structure designed and constructed as part of the wider Bullring development relatively early in the Selfridges design process. This decision allowed each storey of façade to be “hung” from the floor structure above and only laterally restrained at the connection with the storey below. Thus the likely importance of “buckling effects” is reduced, and the loads from the façade can be associated with a particular supporting floor, simplifying the analysis of the combined structure (figures 284, 285) (The Arup Journal, 2005).

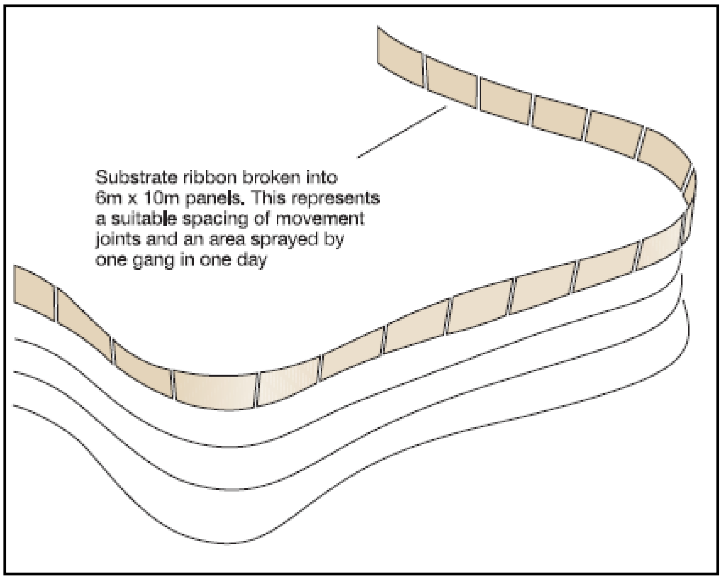


Figure 284: Façade substrate penalization, (The Arup Journal 2005).

Figure 285: Spraying the substrate on site, (The Arup Journal 2005).

In terms of "façade cladding"; the distinctive façade construction covered the sprayed concrete substrate with a "liquid membrane vapor barrier, insulation, and an outer, spray-applied, colored membrane on a glass reinforced render". Finally, the building was clad in "15 000 anodized aluminum discs", each of which went through stringent quality control (figure 286, 287) (The Arup Journal, 2005).

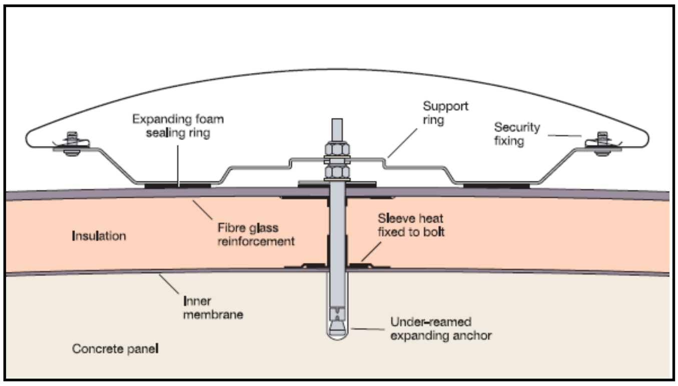


Figure 286: Indicative detail of façade construction and fixing, (The Arup Journal 2005).

Figure 287: façade details and the Glazing at terrace-level entrance, (The Arup Journal 2005).

The final step was the curved bridge which is the 37m span "footbridge" was driven by the architectural aspiration for an elegant form with a clear relationship to the Selfridges building. By using the structure as an "exposed sculptural surface" the design team could minimize the "deck depth" and avoid the need for additional cladding. The bridge is a "steel box girder with internal stiffeners", curved both on plan and elevation, akin to an aero plane wing. Further support is given by cable stays tied back to the Selfridges frame at roof level. By the aid of "rhino software" three-dimensional model was produced to demonstrate that the deck could be fabricated entirely from warped but developable steel plates and segments of bent tubes. This model was also used to produce developed cutting patterns for the "warped surfaces" and to extract all other fabrication information. The bridge was analyzed in "GSA using a 2-D finite element model derived from the Rhino geometry, and detailed design carried out to *BS5400* by slight adaptation of clauses intended to justify conventional rectilinear box girder sections" (figure 288, 289) (The Arup Journal, 2005).

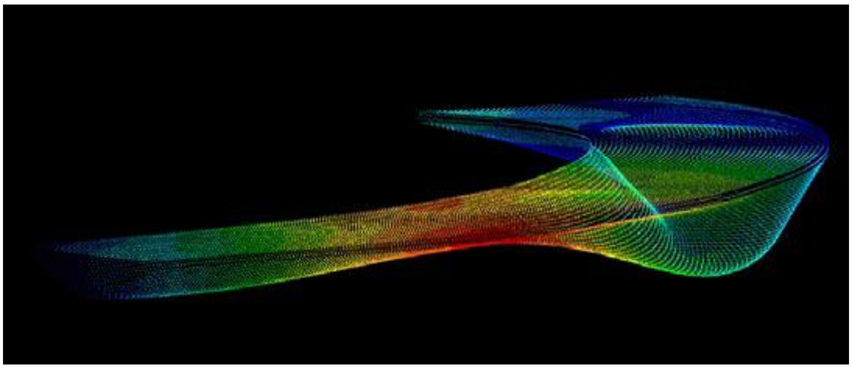


Figure 288: Using GSA during the design analysis
(Source: www.future-systems.com)

Figure 289: Pre-fabricating the bridge elements,
(Michael Stacey, Philip .B and Vincent .H, 2004)

Figure 290: Completed bridge of SELFRIDGES BIRMINGHAM, (The Arup Journal 2005).

Figure 291: (right) view during midnight, (left) interior view inside the bridge, (The Arup Journal 2005).

The bridge is covered by a polycarbonate canopy supported off a series of T-section steel arches at varying angles of inclination, supported in turn by the bridge deck and restrained laterally out of plane by connection to a continuous handrail. The cross sections of these arch elements vary continuously, allowing the tops of the Ts to lie parallel to the freeform canopy surface whilst the stems remain in the inclined plane of each arch. For this reason the arches were also built up from plate with developed cutting patterns for the top plates generated from the Rhino 3-D model. Finally, after investigating Selfridges Birmingham the projects asserted the objective of the study of using the technological techniques as well as using computer methods will aid to make such a complicated form possible to innovate.

7.8. Case (8):

Taichung Metropolitan Opera House, Taichung City, Taiwan, by TOYO ITO

7.8.1. Design Concept

"Architecture has to follow the diversity of society, and has to reflect that a simple square or cube can't contain that diversity." (Toyo Ito)

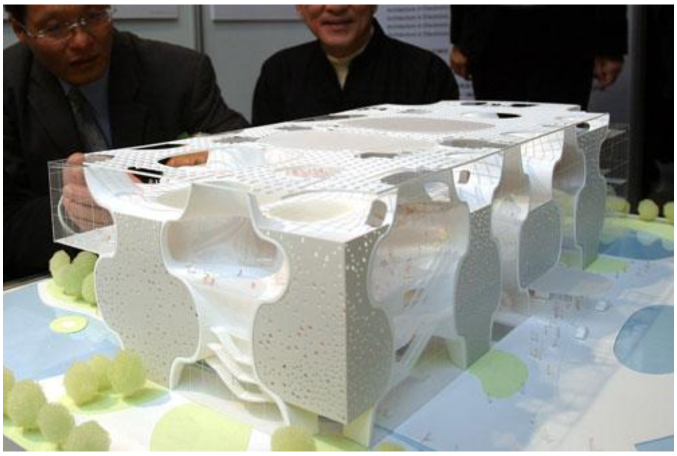


Figure 292: Taichung Metropolitan Opera House, Toyo Ito, Taichung City, Taiwan
(Source: http://www.forgemind.net/xoops/modules/news/print.php?storyid=650)

The design is an open structure which actively engages its surroundings in all directions. The "*Sound Cave"* as Ito calls it, is both a "horizontally and vertically continuous network" that making the building to has more than one front, inviting people from several sides into a "labyrinthine" network of diverse spaces [45].

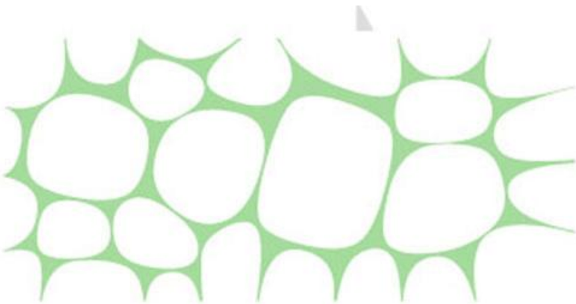


Figure 293: The main concept of Taichung Metropolitan Opera House, Toyo Ito
(http://forgemind.net/xoops/modules/news/article.php?storyid=663)

Figure 294: Site plan showing the connectivity between inside and outside.

(http://forgemind.net/xoops/modules/news/article.php?storyid=663)

7.8.2. Design Process

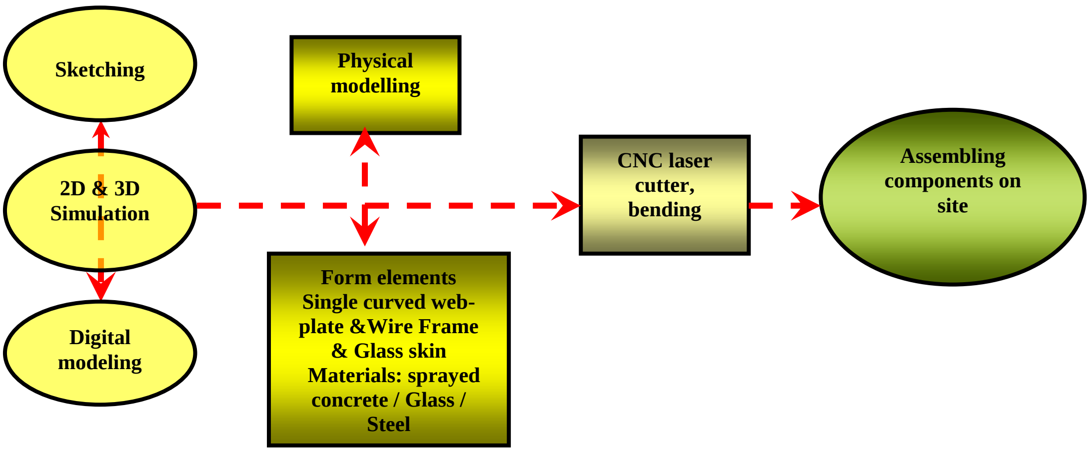


Figure 295: Toyo Ito design process of Taichung Metropolitan Opera House.

Generally; the technique of Ito's drawing can be ordered by starting sketching for crating the main concept as well as using three dimensional scanner, then preparing the two dimensional drawing which is used also for three dimensional simulation. After simulation has been done, the three dimensional modeling is taking the place of visually presenting the proposed form both internally and externally. Then he physically models the main form for testing and feeling of scale. Subsequently; the form components is defined in large scale to be sent directly to the fabrication machine which cut, bend or bending the parts.

Figure 296: Site plan and three dimensional model

(http://forgemind.net/xoops/modules/news/article.php?storyid=663)

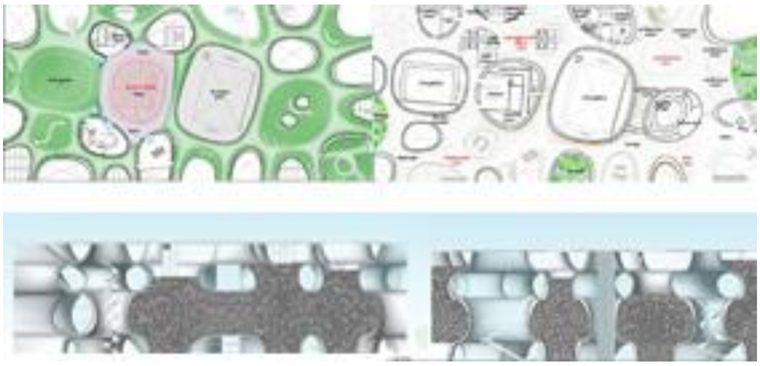


Figure 297: Scaled plans and elevations.

(http://forgemind.net/xoops/modules/news/article.php?storyid=663)

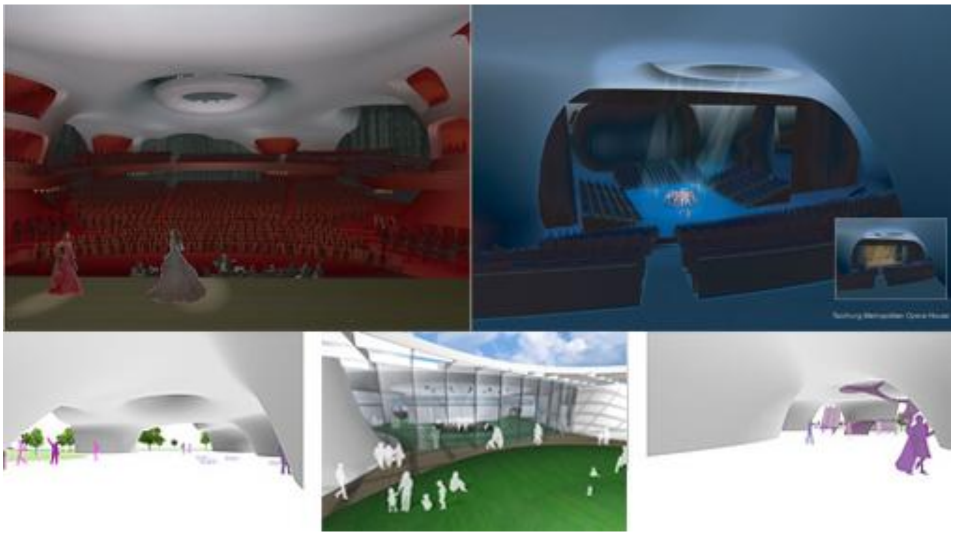


Figure 298: Interior and exterior digital models.

(http://forgemind.net/xoops/modules/news/article.php?storyid=663)

In terms of form shape and the sound reflection, he studied the problem of "sound reflection" as the form is taking an organic shape by using computer simulation technique based on "ray trace method" to investigate early "sound reflection which arrives within about 0.1 second after direct sound arrival", which is closely related to clarity and acoustic conditions for classical music which is also the main activity in the project [46].

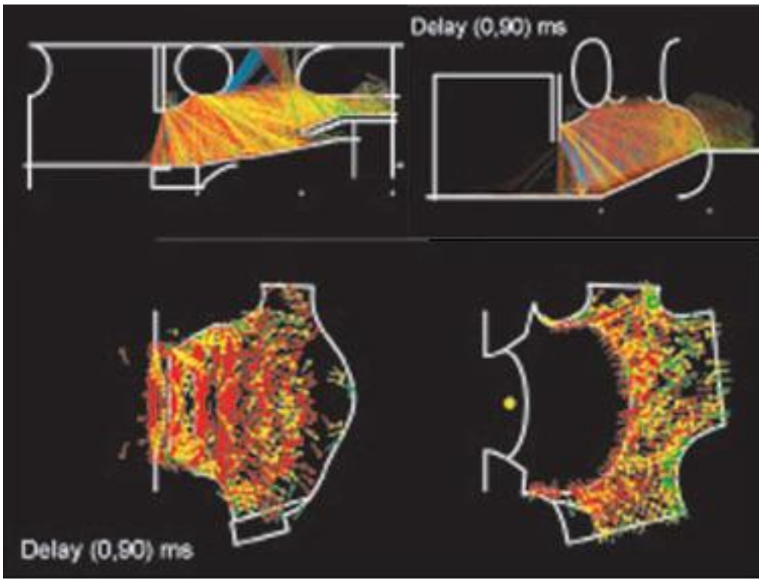


Figure 299: Using computer simulation for acoustic conditions.
(http://forgemind.net/xoops/modules/news/article.php?storyid=663)

Figure 300: Rapid prototyping (RP) physical modeling.
(http://forgemind.net/xoops/modules/news/article.php?storyid=663)

7.8.3. Structure Elements and Details

The proposed structure system basically defined by the double surface structure which is derived by the architectural program requirements and the construction rationality that balancing between freedom of form and structural efficiency. The double surface is proposed to be shotcrete (spray concrete) structure coupled by the simple steel structure utilized as a temporary support for the construction.

The spatial complexity is based on a few simple geometric rules. A membrane between two surfaces is divided into alternating zones A and B. As the surfaces are pulled apart, two continuous spaces A and B evolve, separated by the curvilinear membrane. Repeating this process once more on top of the first, two horizontally and vertically continuous spaces A and B emerge between this one continuous membrane.

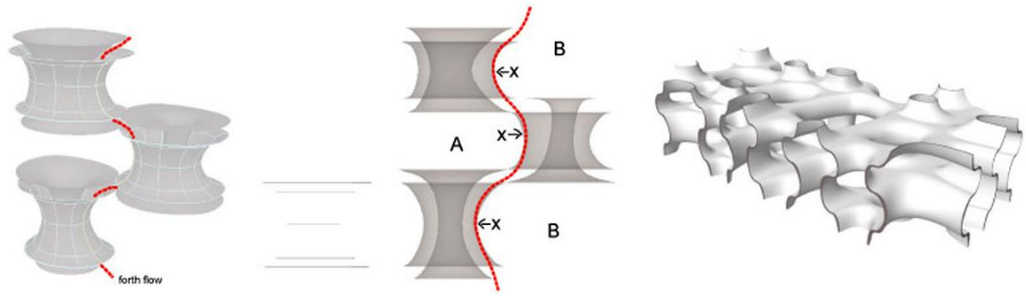


Figure 301: The proposal of double surface continuity.
(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

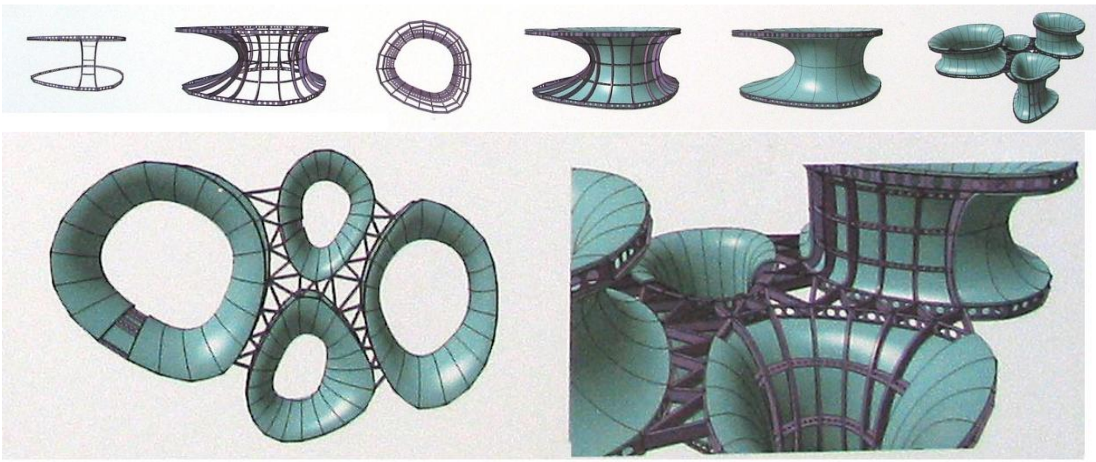


Figure 302: Samples of the form elements.
(Source: http://www.forgemind.net/xoops/modules/news/print.php?storyid=650)

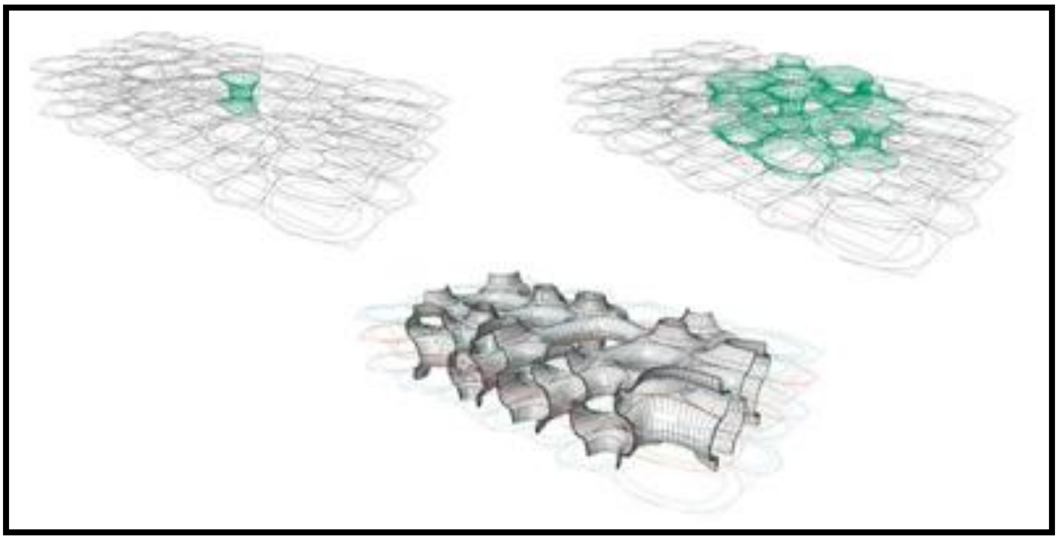


Figure 303: The structure system.

(Source: http://www.forgemind.net/xoops/modules/news/print.php?storyid=650)

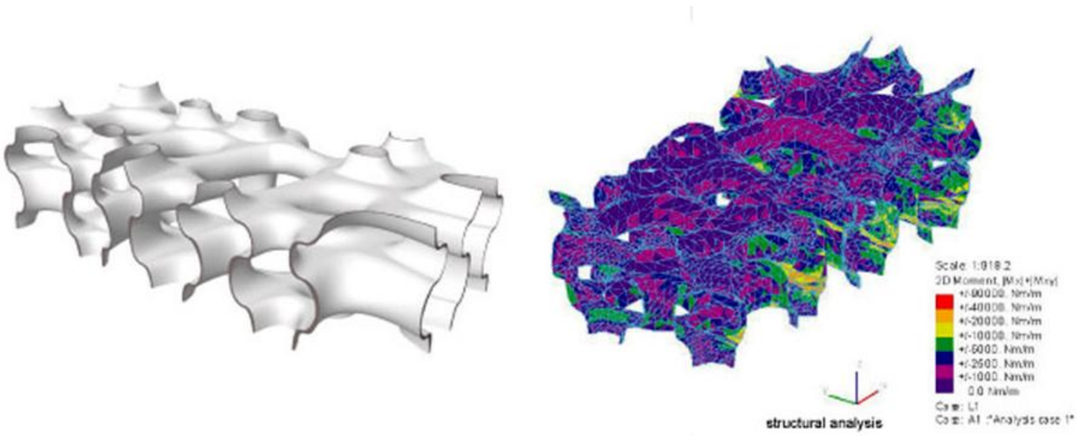


Figure 304: Structural analysis.

(Source: http://www.forgemind.net/xoops/modules/news/print.php?storyid=650)

The elements of the form can be identified as follows:

- Single curved web-plates
- The frame
- The wireframe
- The exterior glass skin
- The used materials which are; sprayed concrete, steel and glass.

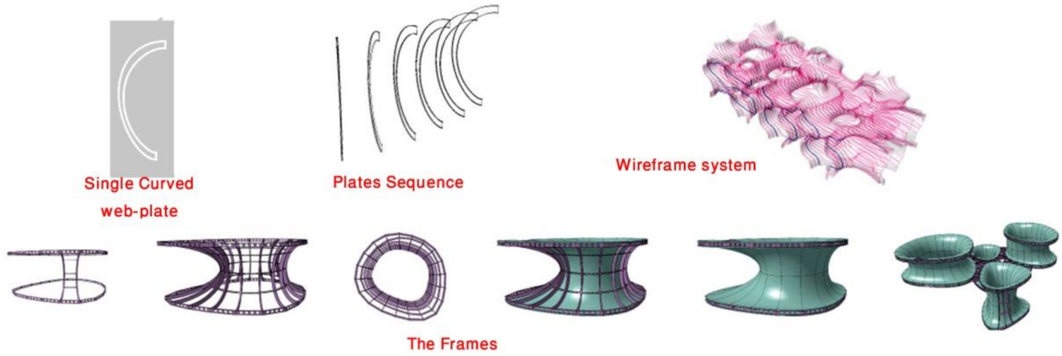


Figure 305: The form elements.

(Source: http://www.forgemind.net/xoops/modules/news/print.php?storyid=650)

7.8.4. Construction Process:

The structure system is developed together with the construction method to realize the free-form geometry in rational and efficient manner. The freeform concrete surfaces are “shotcrete” (spray concrete). It is commonly utilized for tunnel construction and suitable for curved surfaces. It can be “shot horizontally or vertically”, rather than constructing doubly curved framework that is expensive and time consuming on site, the temporary structure in the “void” creates faceted surfaces that best fit the finished surface. Between the temporary “steel work” and the “expanded metal mesh” is the expanded mesh spans to act as faceted framework. The used material is “concrete” with thickness varies between 200mm at the top floor and 350mm at the bottom floor [47]. The process of fabrication can be summarized as following:

1- The curved web plates are cut out from the steel plate with the method of laser cutting.
2- Other plates as a flange are weld on the web plate, following the curve of the web plate.
3- Each frame will be set up by following the curvature of building geometry.

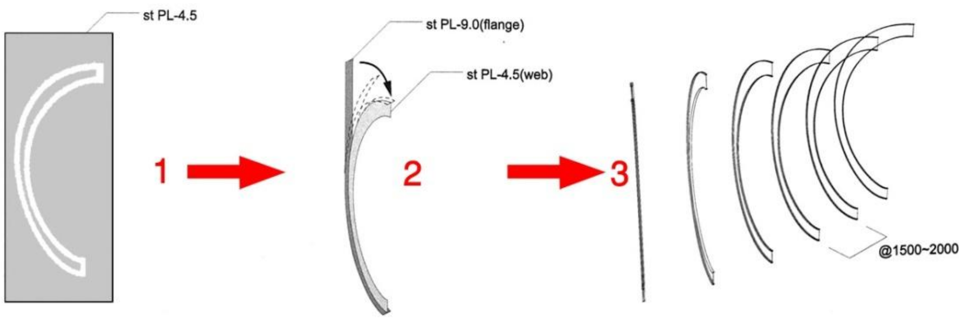


Figure 306: Setting up the frames.

(Source: http://www.forgemind.net/xoops/modules/news/print.php?storyid=650)

4- They are connected with each other by the horizontal frame and the basic form is created.
5- The “shotcrete” (spray concrete) is applied on the expand metal mesh installed in the both sides; which make it possible to realize free-form surfaces without an installation of the complicated frameworks [48].

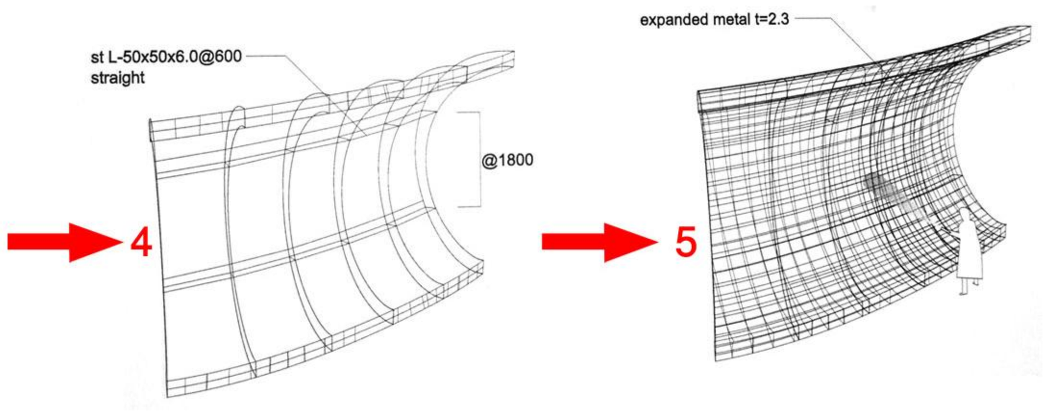


Figure 307: Completing the framework

(Source: http://www.forgemind.net/xoops/modules/news/print.php?storyid=650)

7.9. Case (9):

Taichung Metropolitan Opera House, Taichung City, Taiwan, by Zaha Hadid Architects

7.9.1. Design Concept

Taichung Metropolitan Opera House is awarded as a second prize competition of Zaha Hadid contribution in Taiwan after the first winner Toyo Ito. Zaha hadid is presently one of the most successful professionals working with the concept of form being a field of flows and fluidity with which the form can be created. Many of her recently works touch upon the theme of How to produce complex deformations in surfaces and this is what she was trying to express in this project.

The expressiveness for her ideas and drawing which based on three dimensional representation and digital techniques has pushed her to be among the other pioneers of the digital age. Although her contribution in this competition was considered as the second prize, the process of her design should be studied because of the technique and theoretical used.

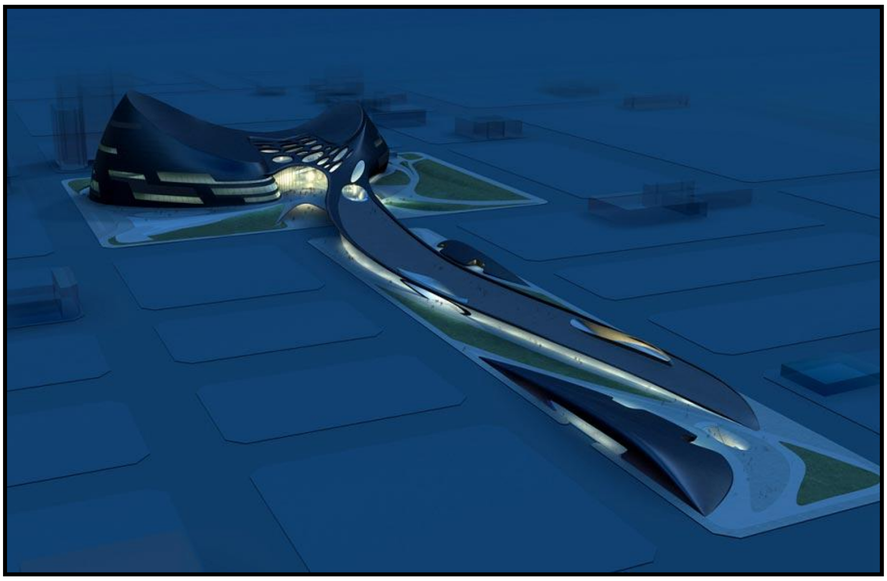


Figure 308: Zaha hadid's concept of Taichung Metropolitan Opera House

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

7.9.2. Design Process

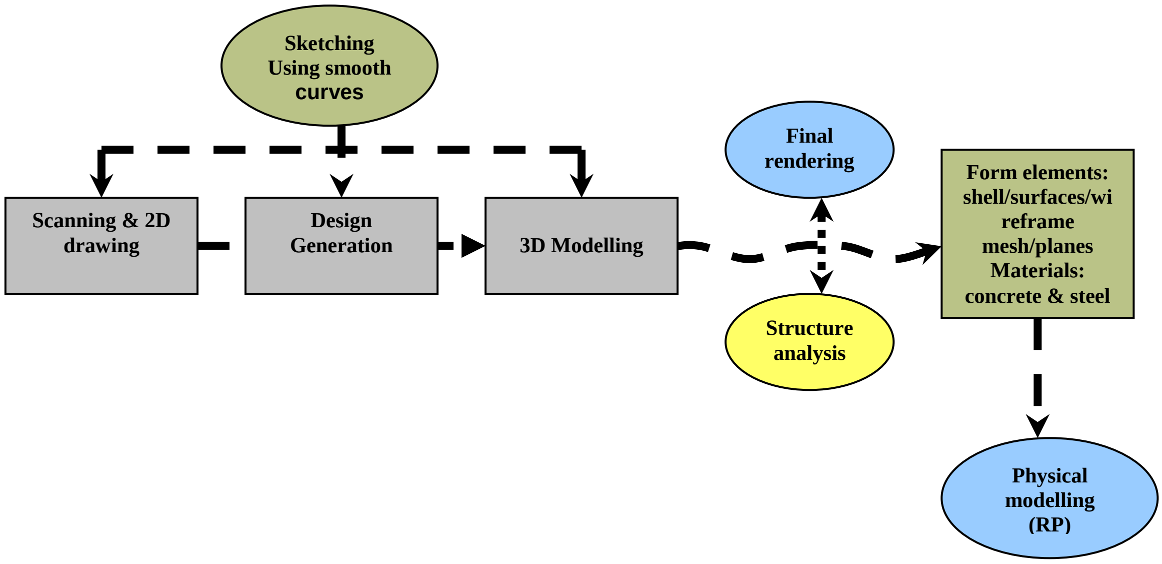


Figure 309: Zaha hadid's design process of Taichung Metropolitan Opera House.

Zaha hadid process of design for every project starts from "hand sketching" which could be then scanned into the computer for the stage of design generation. As she asserted in an interview with the Chairman of architectural association school of architecture Mohsen Mostafavi "I still think that even in our later projects, where the computer was already involved, the 2-dimensional plan drawings are still seminal" (El Croquis 103). But at the same time this does not means the techniques of computer are undesirable at hadid's process, however; as she claimed "I'm setting with 15 or 20 computer screens in front of me and I can see them all at the same time, it gives me yet another repertoire. You can see at the same time the section, the plans and several moving 3-D views, and in your mind you can see them in yet different way" (El Croquis 103). Which means that the ability of computer at her process improves the designer's imaginary during the design process.

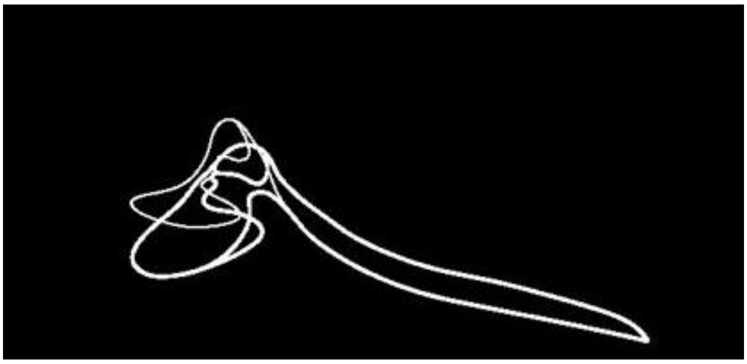


Figure 310: Zaha hadid hand sketch of Taichung Metropolitan Opera House.

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

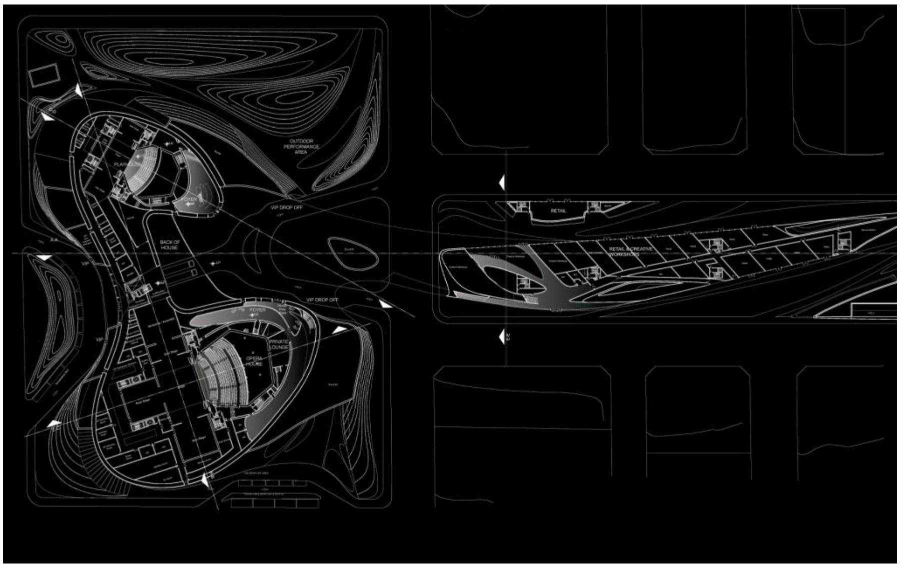


Figure 311: Zaha Hadid's two dimentional plan drawing.

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

The new digital design tools have had an important and increasingly influence on the work of Zaha hadid. Consequently; after the completion of sketching, Z.hadid starts using the computer tools as an architectural language such as using smoothed curves instead of using straight lines which made her composition to act as a single continuous surface that facilitated the over all movements of the public which is one of the most important factors in her concept (figure 312).

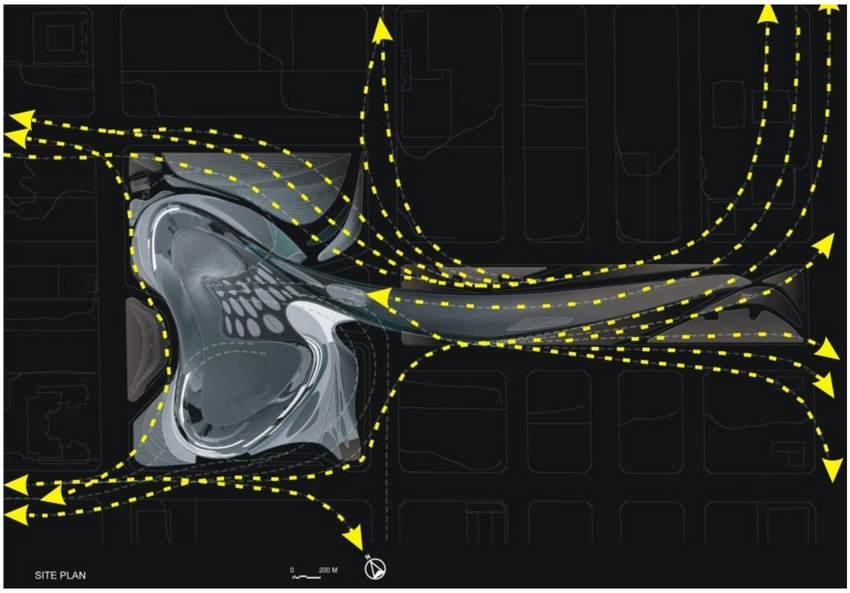


Figure 312: The site plan indicates the set of smoothed curves.

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

The main form was formed by the transforming the genetic shape into six stages of transformation. The last transformation ends when the required form reacts compatibly with the site boundaries.

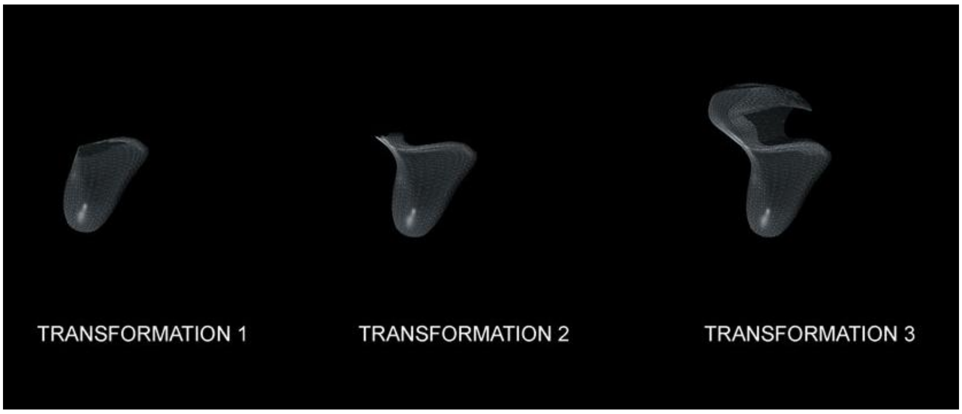


Figure 313: The first three stages of transformation.

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

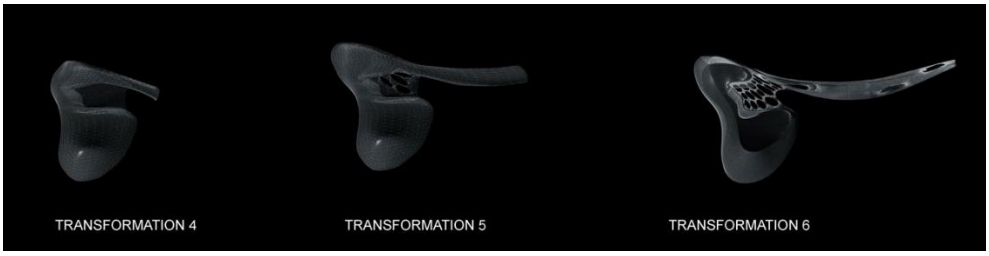


Figure 314: The last three stages of transformation.

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

Another factor of Z.Hadid design process is the technique of layering and concomitant technique of rendering elements as transparent to reveal the depth of the composition. The transparent superposition of the drawing elements illustrates the complicated elements of the form structure which later facilitates the process of fabricating the structural parts during the production process. The structure elements can be divided into four categories; the shell/ exterior surface, the wireframe mesh structure (the grid), deep steel beams and the planes which are the floor slabs.

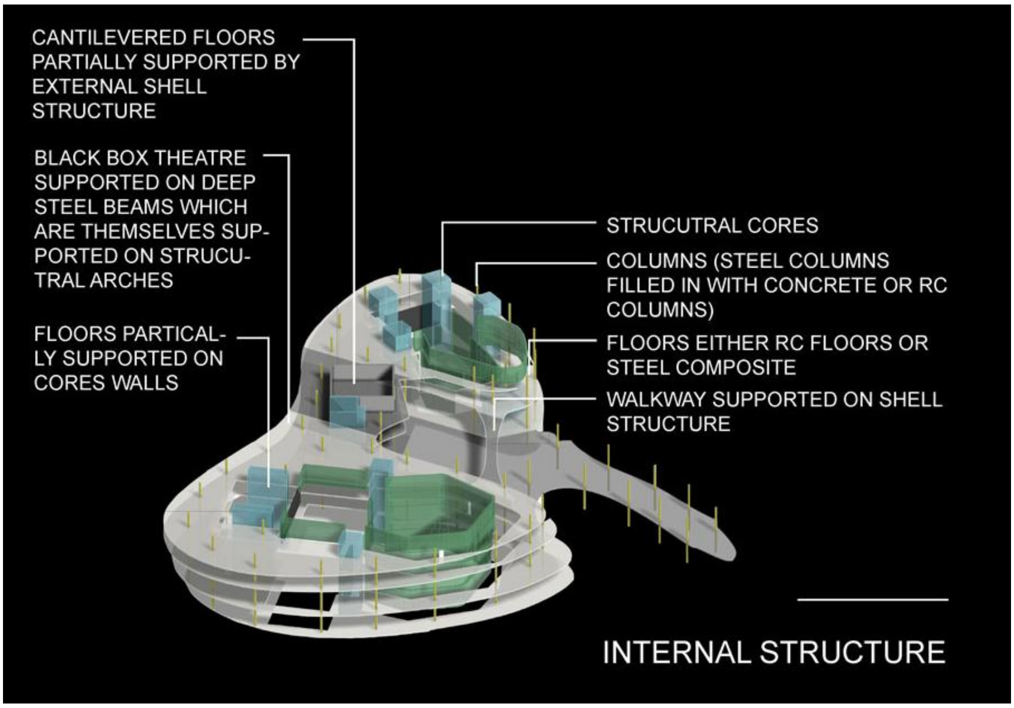


Figure 315: Internal structure analysis

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

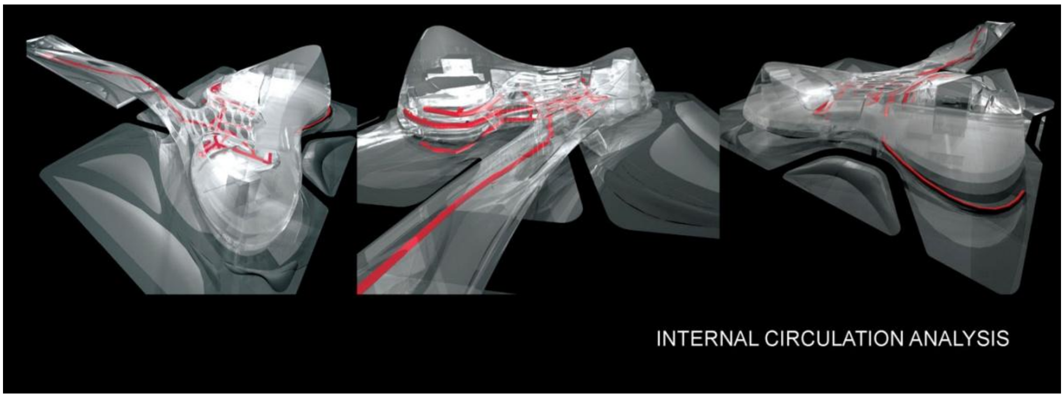


Figure 316: Internal Circulation (movements) analysis

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

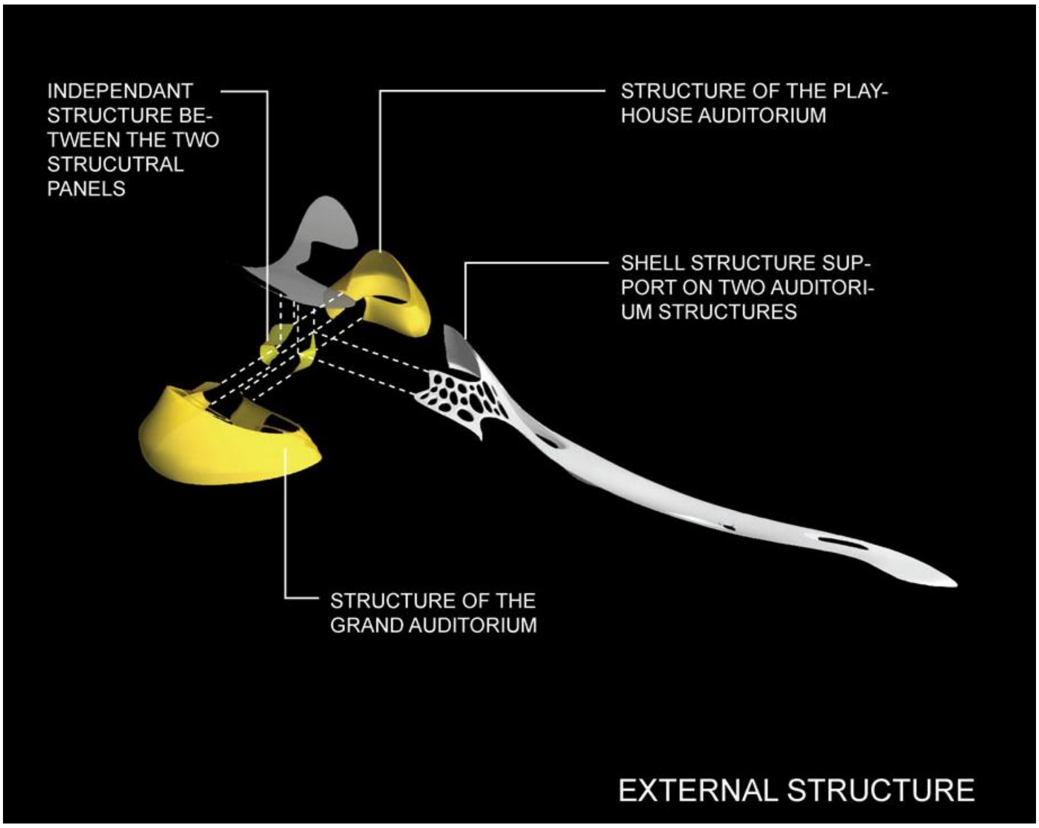


Figure 317: External structure analysis.

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

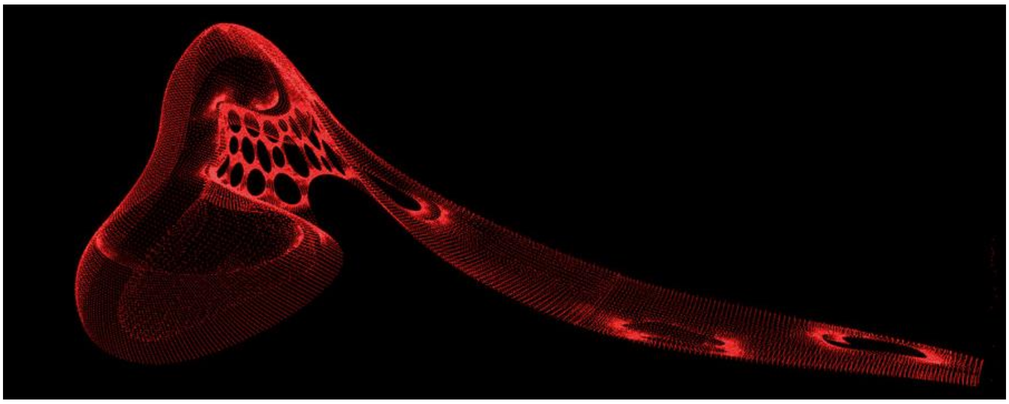


Figure 318: Wireframe mesh of the structure

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

After generating all the design components, the final form was rendered and textured with the types of decided materials. At this stage Z.Hadid prepared several three-dimensional models that have been taken from different views which are the specialty of her process.

Figure 319: Three-dimensional models of Hadid's Taichung Metropolitan Opera House

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=663)

7.9.3. Construction Process

The Taichung Metropolitan Opera House of Zaha hadid is a competition project has been taken as an example to clarify the given techniques of digital fabrication process as mentioned in chapter six. Z.Hadid and here team have decided to physically modeling their concept by the process of rapid prototyping (RP). The continuity of the surfaces and the smoothed edges of the form couldn't have been done without the aid of rapid prototyping machines. Thus; by using the 3D printing, FDM machine and milling machine they created their physical model as shown in the figures follows.

Figure 320: Completed Physical model of Taichung Metropolitan Opera House by Zaha hadid.

(Source: http://forgemind.net/xoops/modules/news/article.php?storyid=650)

CHAPTER EIGHT

CONCLUSION

8.1. Thesis Findings

In this last section of the study it has been reached some several factors that have affected the evolution of effective architectural form during the previous decade, which in turn contributed significantly Clearly, the development of the design and production of digital architectural forms, which is the thrust of this study. The evolution of architectural form and entry of new technologies through the design and production process has provided an unprecedented improvement in architecture and this is what will be summrized during this final section of the search.

8.1.1. Qualities and Importance of Form

From the reading of many texts involved in the case of form in architecture such the book of “FRANCIS D.K CHING,1996” who was concerned with form, space, and order; and the “Roger H. Clarck & Michael Pause, 1985” who also involved in discussing the basic elements of present architecture in their book “PRECEDENTS IN ARCHITECTURE”; and the “HYBRID SPACE” by “Peter Zellner, , Thames&Hudson, 1999” that discussed the new forms in digital architecture; also the “Materials, Form and Architecture” by “ Richard Weston, 2003” and some other online articles which discussing the given topic; it has been found that the form has a huge impact on the architectural context becauce it covers the whole; also is considered to be the critical means of architecture that comprise a design vocabulary that is both elemental and timeless. Therefore; the qualities and the importance of form can be perceived from several points:

- Physically: the form is considered as the first physical element that we can see and perceive.
- Visually: the form represented by coordinates made up of dots, smooth curves, surfaces and wireframes. By that way architect becomes free of making the decision of construction method in the first place.

- It defines the space and the context where our activities are taking place.
- Also can be considered as the only element in architecture which connect the inside and outside.
- All the perceptual elements such as dimensions, scale, the quality of light, the quality and the substance of materials and other spatial boundaries are defined by the elements of form and can not be defined without the existence of form.

8.1.2. Advanteges of using Computer Technologies

Along with the growth of computer technology, the improved technique of computer has assisted the designer during the design process in several ways whether in the design exploration, representation or construction process. After the investigation made at the beginning of the study on how the CAD/CAAD has been improving through the history of architecture, as well as how the CAD/CAAD techniques introduced to the field of architecture, it has been found that the technique of computer in architectural design has several qualities and advantages in terms of use during the design process. These advantages can be summarized as follows:

- Re use of design components
- Ease of design modification
- Automatic generation of standard components of the design
- Validation/verification of designs against specifications and design rules
- Simulation of designs without building a physical prototype
- Automated design of assemblies, which are collections of parts and/or other assemblies
- Output of engineering documentation, such as manufacturing drawings, and Bill of Materials
- Output of design directly to fabrication facilities. In other words; Outputting directly to a Rapid Prototyping or computer numerical control Machine for industrial prototypes which is called the “file-to-factory” as mentioned at the last two chapters.

- Three dimensional computation extends the architect's vision by permitting a wide range of experimentation of the forms seem impossible, improves the architectural language, changes the concepts of architectural debate, and provides various tools which opens various dimensions in the architectural design.
- By the use of new computer techniques, new elements of form have been emerged which are totally different from the conventional elemnets of form such as: Vertex, polygons, surfaces, wireframe, meshes, and skin.
- Computers are not just used in graphical stages of design production, but are used in every step of the construction process.
- Opening the way for the inventors and creators of many opportunities to discover new techniques in architectural design besides trying to validate architectural thinking in a different realm.
- "Using the computer soft wares in the design process or visualizing the design's concept seems to be more like shaping clay"; also "the computer has not only facilitated a new means of production but encouraged an examination of the very process by which the studio generates its work and distributes project information, both internally and externally" as said Morphosis (Peter Zellner, 1999). So that means working digitally has given more flexibility to the architectural design.
- "The computer has enabled the emergence of genuinely new morphologies, both in the translation of complex series of forms into a logical construction sequence, and as a means of looking at the results of exploration" Mayne said (Peter Zellner, 1999).
- Using digital techniques enabled the ability of facilitating the mathematical description of the complex forms geometries, also the optimization of the construction process.
- The discovery of animation techniques has brought the "solution of moving the architecture away from its inert logic of stationary relations into an operative rhythm of transmission and interaction" (Greg Lynn, 1998).
- It can be seen that using the computer techniques in architecture has completely shifted the way of thinking and experimenting the architecture into a new realm which made any type of form seems impossible to be done.

8.1. 3. Assistance and Supplementation of Digital Architecture in the Design Process

During the extensive study on the phenomena of digital architecture starting from the early existence of digital thoughts through the recently concepts of digital design, the study has found that the assistance and supplementation of digital architecture can be summarized as follows:

- by the emerging of digital architecture new design tools have been discovered such as three-dimensional software and digital fabrication machines that enhancing the architectural practice in different context; e.g. drawing, modelling, simulation, design collaboration, construction management and building fabrication which now routinely performed by using digital technologies.
- The influences of digital architecture and the use of new technology on the design process can be obtained from; making new modes of expression, shortening the planning phases; new ideas can be explored directly by three-dimensional objects or spaces without translation into two-dimensional drawings, and an increased number of design alternatives can be generated.
- Another aspect has been gained from the emergence of digital architecture and technology which is the reconfiguration between conception and production. In other words; the creation of direct link between what can be conceived and what can be built through "file-to-factory" process (Branko Kolarevic, 2003).
- The supplementations of digital technology on the design process, design presentation and construction process have reduced the gaps of discussion between the designer and client, the architect and builders and so on.

8.1.4. Advantages of Using Digital Tools in the Design Process

According to the results mentioned in chapter five that how much difficult to incorporate the digital tools in both the studio-lab of schools or design offices as a design solution for model making during their design process, on the other hands; the study investigated that what are the positive effects if the schools and office had the chance to access or use those tools whenever they need. Additionally; if those tools are so costly to be used in architectural practices and construction process, so why they considered today as the best solution in both design and construction process. The following points are the discovered advantages on using digital tools as a method that improved the design and construction process:

1. Designers are physically exploring different designs than they would otherwise be able to with a physical model. If the digital tools was not available, the designs would remain in the computer as digital models or be physically represented in a much rougher, imprecise manner.
2. Designers are now using this technology to confirm the quality of their digital models.
3. Designers are exploring more designs in a shorter amount of time.
4. Designers are evaluating their designs in a range of scales from a single model. Since a digital machine requires the designer to create a 3D digital model, that single model can be printed at a variety of scales, ranging from details to urban sites.
5. Demonstrates design possibilities using small scale models manufactured on digital devices.
6. Using digital tools (CAD/CAM) provide producing more accurate free form models.
7. Building constraints are discovered before physical construction begins, and these constraints can be used as rules in a generative system which then reduces the undesirable results on real time process.
8. As the machines are so costly in terms of single price and annual maintenance, also as the time is very importance during both designing and constructing because “the time is money”, so using digital fabrication machines as an essential tools during the design and construction process leads to reduce the time of

construction so the cost of construction will be reduced as well which means that digital fabrication machines can also be economical. The chart bellow is a financial plan of a project by two construction process (with and without digital fabrication machines) to illustrate who digital fabrication machines reduced the time and the cost of construction.

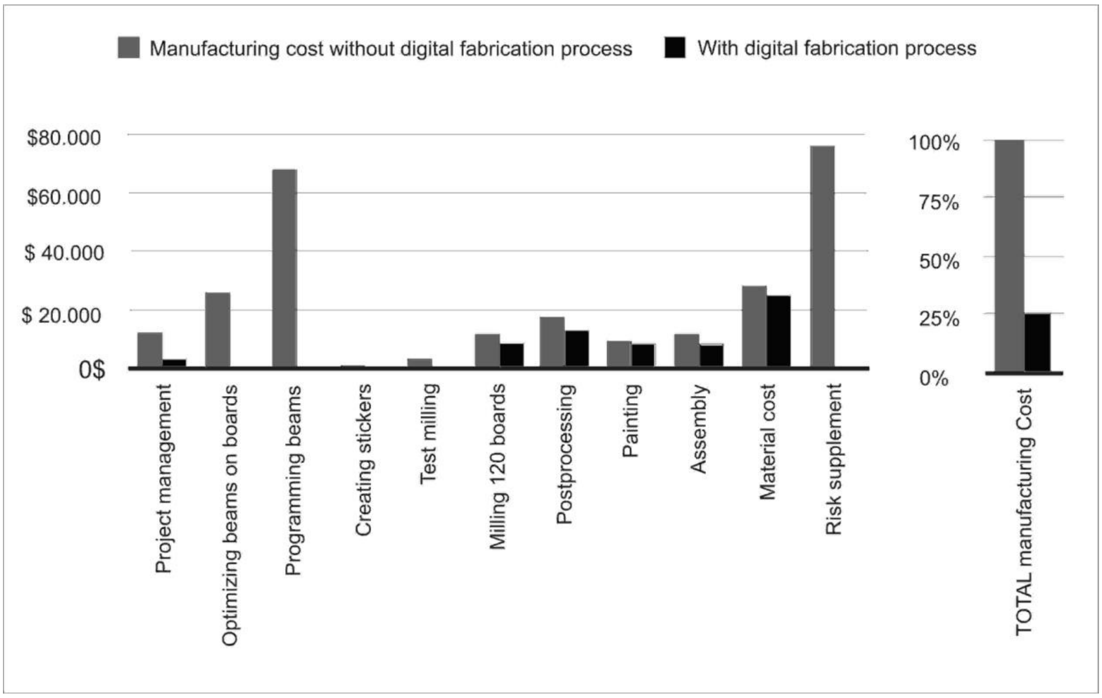


Figure 321: Reduction of time and cost using digital fabrication process.
(Source:http://urbandesign.ethz.ch/twiki/pub/Main/ChristophSchindler/2006_Schindler_InventioneeringArchitecture.pdf)

8.1.5. Digital Production Chain:

The challenge of this thesis was to experiment the new design strategy and a new way of thinking by the aid of digital technologies. It was not aiming at offering a specific architectural solution but at exploring the connection between what can be design and what can be build through digital design process.

Using computer techniques during the whole design stages doesn't suggest abandoning the craft of drawing by hand; this some think unlikely to ever happen, but by exploring the digital capabilities the architects now have a wide rang of new architectural shapes, objects or; in other words, possibilities that were impractical before the computer. In addition, although it seems that the design chain involves a kind of arbitrary process for generating the form, the truth is that the input of parameters, the decision making for interdependencies and any design interventions belong to the architect or designer. The result might be unpredictable because of the different interacting methods and techniques but that is what makes the process of digital design more inventive and interesting.

To sum up; as the thesis aimed to trace the process of creating digital form from the early design stages to production at which the form became physical, the study has reorganized the production process of digital form into one chain which indicates the individual design stages. The digital chain is the uninterrupted working methodology, where the computer is used as both a design tool, and a methodological medium. The digital chain is a cumulative process of design, generation, detailing, testing, processing, fabrication, assembling, and finally construction. Therefore; it seems that architecture that is derived through digital processes has the potential to be both more complex and efficient while maintaining irregularity and inventiveness as a design motif.

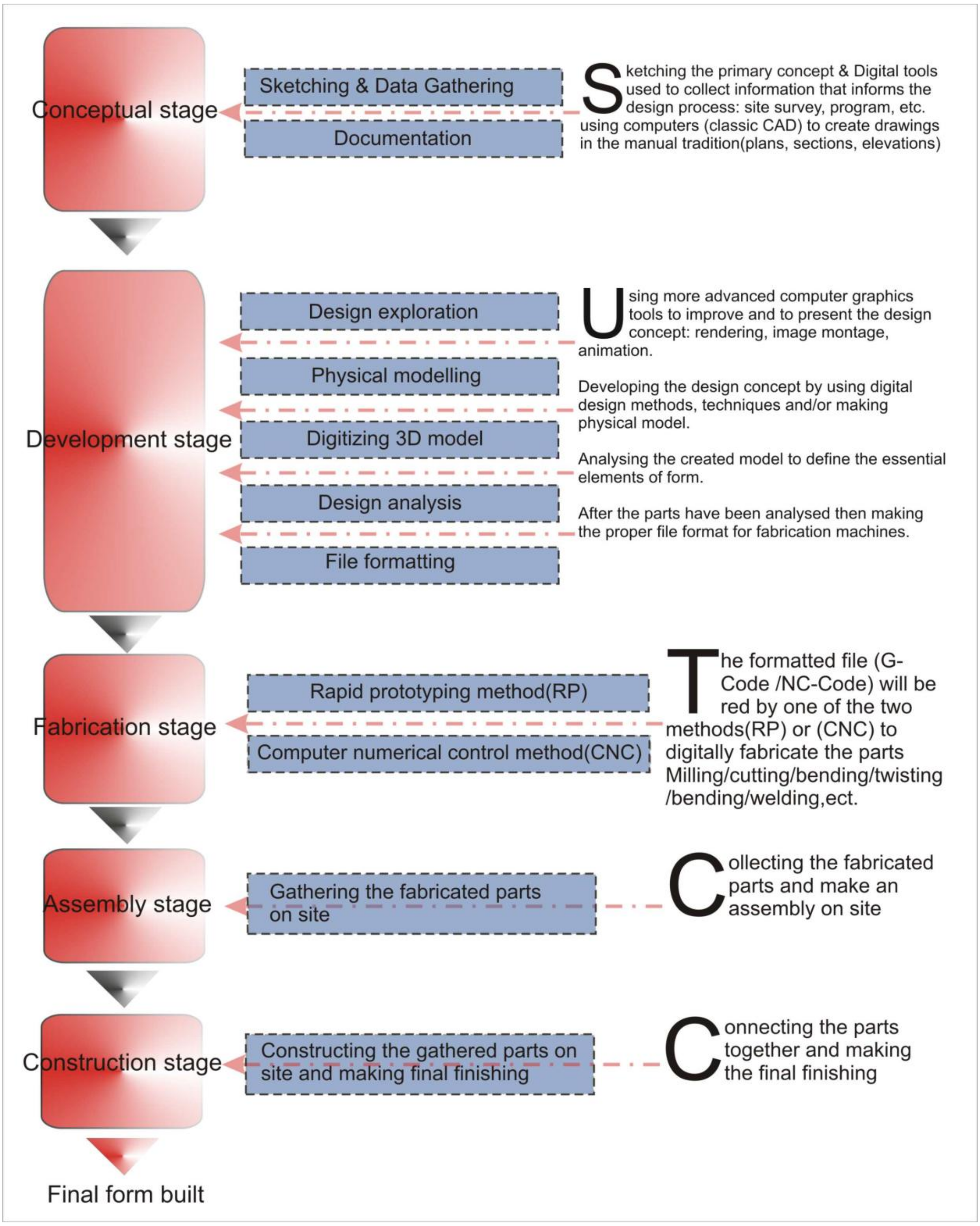


Figure 322: Digital Production Chain.

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GRAPHIC SOFTWARE RESOURCES

- Autodesk® 3ds Max® 9/8 index
- Autodesk® MAYA® 8 index
- Form-Z® version-4 index
- RhinoCeros 3.1® index

LIST OF ABBREVIATIONS

- **(CAD):** Computer-Aided Design.
- **(CAAD):** Computer-Aided Architectural Design.
- **(CADD):** Computer-Aided Drafting Design.
- **(CAM):** Computer-Aided Manufacturing.
- **(CAE):** Computer-aided Engineering.
- **(NC):** Numerical control.
- **(CNC):** Computer Numerical Control.
- **(RP) :** Rapid Prototyping.
- **(MIT):** Massachusetts Institute of Technology [famous American technical college that is located in the city of Cambridge in Massachusetts (USA)].
- **(IFC):** International Finance Corporation.
- **(VRML):** Virtual reality modeling language.
- **(blobmeister):** used by Los Angeles architect Wes Jones to describe the digital architects who use the software as the way modernists used structure.
- **2D:** Two Dimension.
- **3D:** Three Dimension.
- **NURBS:** is an acronym for Non-Uniform Rational B-Splines.
- **PCs:** Personal Computer System.
- **CVs:** Control vertices.
- **SL:** Stereo-lithography Machine.
- **FDM:** Fused deposition modeling.
- **3DP:** Three-dimensional printing.
- **MJM:** Multi-Jet modeling.
- **LOM:** laminated object modeling.
- **GPS:** Global Positioning System.
- **CATIA:** Computer aided three-dimensional interactive applications.
- **IGES:** Initial Graphics Exchange Specification.
- **GSA:** Global Simulation Analysis.